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DECISION ANALYSIS METHODOLOGY APPLIED TO DEEP BASE COMMUNICATIONS

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August 1986

Lawrence Livermore National Laboratory

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NOTATION

BMO	Ballistic Missile Office
C^3	Control, Command, and Communication
ELF	Extremely low frequency, 30 Hz - 300 Hz
EM	Electromagnetic
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
HA	Higher authority
HEMP	High altitude EMP
HF	High frequency, 3 MHz - 30 MHz
HOB	Height of burst
ICBM DB	ICBM Deep Basing
LANL	Los Alamos National Laboratory
LF	Low frequency, 30-300 kHz
LLNL	Lawrence Livermore National Laboratory
MF	Medium frequency, 300 kHz - 3 MHz
RBO	Rapid bore-out (antenna reconstitution using high speed drilling)
SHF	Super-high frequency, 3 GHz - 30 GHz
SREMP	Source region EMP
SRF	Secure Reserve Force
TRW	TRW
TRWD	TRW Document, ICBM DB System Description and Technical Requirements
UHF	Ultra-high frequency, 300 MHz - 3 GHz
VHF	Very high frequency, 30 MHz - 300 MHz
VLF	Very low frequency, 3 kHz - 30 kHz
W	Yield

EXECUTIVE SUMMARY

Deep underground basing of an ICBM facility improves its survivability. The deep basing concept relies on the thick rock overburden to provide it with an "earth shield" to absorb any Soviet nuclear attack. However, this basing scheme complicates the problem of how communication is maintained between the deep base facility and higher authority in a post-attack environment.

This report addresses the identification of what communication links between the underground facility and the surface will be operational in a post-attack environment and will meet the communication requirements of the ICBM deep base. This problem is difficult and complex because of the inability of conventional communications systems to survive and the lack of information about newer systems designed for survival. In addition, there are significant uncertainties concerning nuclear weapons effects, shock propagation, and the influence of geological parameters.

There are numerous communication options for the deep base. In general, these options can be characterized by three general types: proliferated, hardened surface antennas; through-the-earth communications; and reconstituted communications, of which the rapid bore-out option is a specific case. Many of the potential options are costly and incorporate many new and untested technologies. The identification of the preferred option or combination of options is an important step in the deep basing communication system design and could affect overall facility design in terms of basing location, geometry, support systems, and cost.

We have developed a systematic methodology based on decision analysis theory and systems analysis to evaluate the deep base communications options. It is our goal to incorporate the results of HQ BMO sponsored studies (LANL rapid bore-out study and LLNL through-the-earth communication study) into our decision analysis. Also, we wish our decision methodology to be flexible so that future developments in communication options and threat definition can be accommodated.

This report provides an overview of the progress of the decision analysis model development through September 30, 1985. A general outline of the decision analysis approach and its application to deep base communications systems is presented. Procedures for selecting quantitative measures of system performance are discussed and an initial listing of these measures is proposed.

Subsequent reports will evaluate the main classes of communication options for the deep base. It is anticipated that the next report will evaluate the reconstituted bore-out antenna option.

I. INTRODUCTION

ICBM DEEP BASING

Over the last decade, a number of reported advancements in Soviet ICBM development have raised important questions about U.S. ICBM vulnerability. In developing the plan for a nuclear Secure Reserve Force (SRF), several ICBM basing studies were initiated. One promising study is the ICBM Deep Basing (ICBM DB) Program (Boeing, 1980, and Gilbert Associates, 1983).

The ICBM DB concept is a SRF housed deep beneath the surface of the Earth. Conceptually, the thick "earth shield" provides protection against surface attacks and thereby enhances the survivability of the deeply based ICBMs. However, this basing concept complicates the problem of how communication is maintained or re-established with higher authority (HA) in the post-attack environment.

The emphasis of our effort will be the analysis of the various communication options that would be operable in a post-attack environment and are of interest to an ICBM DB concept.

ICBM DB COMMUNICATIONS

Survivability and reliability of communications systems is a concern with any ICBM basing scheme. By placing the base deeply underground, one has the additional problem of how to establish the links from the subsurface to the surface. Simple hard wire links from the subsurface to the surface may not be viable options. In evaluating communication options, our problem is further complicated by uncertainties about the effects associated with a nuclear attack.

There is a wide range of potentially useful options for the ICBM DB communication systems. Many of these options are costly and incorporate new and untested technologies. Several of these communication options are being explored at present. These options are of three general types: proliferated hardened surface antennas or portals; through-the-earth communications (Buettner et al., 1985); and reconstituted communications, of which the rapid bore-out method (Newdecker et al., 1985) is a subset.

The identification of the preferred deep base communication options is a necessary step in the deep base facility design, and the determination of the survivability of the communication system options is critical to proceeding with any potential design.

The deep base communications system is composed of two main segments: internal communication between manned basing stations and communication between the underground missile facility and higher authority (HA). The focus of this report is on the communication with HA.

DECISION ANALYSIS

Decision analysis is a systematic procedure for approaching complex problems that include many uncertainties as well as many alternatives. It helps reach solutions by using analytic techniques from decision theory and systems analysis. It also provides quantitative methods for evaluating decisions when there is a large degree of uncertainty in performance. When considering the large number of alternative communication system options, decision analysis helps in evaluating the relative merits and drawbacks of each option.

REPORT ORGANIZATION

This report describes the basic structure of our decision analysis approach. In subsequent reports, we will apply the decision analysis approach to the three main categories of subsurface to surface communication options, namely, hardened surface antennas, low frequency through-the-earth, and the reconstituted antenna using high speed drilling technology. Technical details are deferred to the appendices.

The report consists of six major sections. The first section gives a brief introduction to the deep base communication problem and to decision analysis. The second section, "Overview of the Decision Analysis Model," gives a general outline of the decision analysis approach and its application to deep base communication systems. The third section, "Performance Measures," describes the progress on identifying the quantitative criteria by which the communication systems are assessed. The fourth section, "Nuclear

Weapons Effects," discusses the considerations needed in defining and quantifying the nuclear attack threat facing the communication systems. Section five, "Communications Options," lists and discusses the communication options currently identified for decision analysis evaluation. Finally, the sixth section provides a summary and statement of future efforts.

II. OVERVIEW OF THE DECISION ANALYSIS MODEL

DECISION ANALYSIS APPROACH

We are using decision theory to provide a logical structure for representing various factors relevant to a decision, such as alternative options and threats, and possible outcomes. In addition, our approach provides quantitative methods for evaluating decisions when uncertainty is an important factor. The theory also prescribes how to use information that reduces uncertainty. This can assist in identifying areas where additional R&D is needed.

REASONS FOR CHOOSING THE DECISION ANALYSIS APPROACH

Deep base communication system decisions are inherently difficult with pervasive uncertainties and complexities. Several important aspects of the system performance and the Soviet threat are uncertain. While a deterministic approach generally simplifies the calculations, it may mislead decision makers by obscuring the potential magnitude and implications of uncertainty about performance and survivability of various options. Decision theory furnishes explicit methods for taking these uncertainties into account. Since there are limited data about many of these uncertain factors, decision makers must often rely on expert judgments. Decision analytic models provide a means for incorporating expert judgments and for determining the effects of differing views.

Further, when analyzing the deep base communications problem, one must consider a large number of alternative communication systems. It is especially critical that the evaluation methodology has the ability to trade off the relative merits and drawbacks of each communication system option. The decision analysis approach affords systematic procedures for modeling these trade-offs and for evaluating and comparing a large number of alternatives.

Another reason for using decision analysis is its logical approach to quantifying the performance of a deep base communications system. For example, the framework we have developed gives explicit definition to the concepts of survivability and reliability, and provides models to quantify those characteristics of a communications system. Further, since many of the system alternatives are still in the R&D stage, the "value of information" concept from decision theory, mentioned above, can be used to quantify the potential benefits of additional R&D.

The decision analysis approach has proved useful in several similar problems, including nuclear material security and safeguards, defense systems design and procurement, corporate strategic planning and competitive analysis, research and development planning, etc. In these applications, decision analysis has furnished the logic for thinking through complex decisions, improved communication between technical experts and decision makers, and produced insights that led to better decisions.

DECISION PROBLEM

In designing deep base missile facilities, a choice must be made between a wide range of potential communication systems for deep based ICBMs. Unfortunately, conventional hard wired communication systems linking the deep base to the surface are highly vulnerable to ground motion, surface blast, and unless extraordinary means are taken, to EMP. As a result, alternative communication systems have been proposed that dispense with a fixed hard wire link to the surface or that survive through proliferation. This decision problem is represented by the decision tree in Fig. 2-1. The choice of options is based on system performance and the relative values thereof. The performance is highly dependent on the effects of the nuclear weapons attack.

Basic concepts of alternative communication systems being explored at present are the reconstitution of the high data rate system through high speed drill, or more commonly known as the "rapid bore-out" (RBO), low frequency through-the-earth communications, and proliferated, hardened surface antennas. Other communication system options can be constructed from these basic concepts. The principal question to be addressed is how will the deep base reliably communicate with the outside world, in particular, in a post-nuclear attack. Dispersed fiber optic systems - either as a direct link or a connection to a surface antenna, and combined through-the-earth plus hard wire systems are examples of hybrid system concepts. Our decision analysis

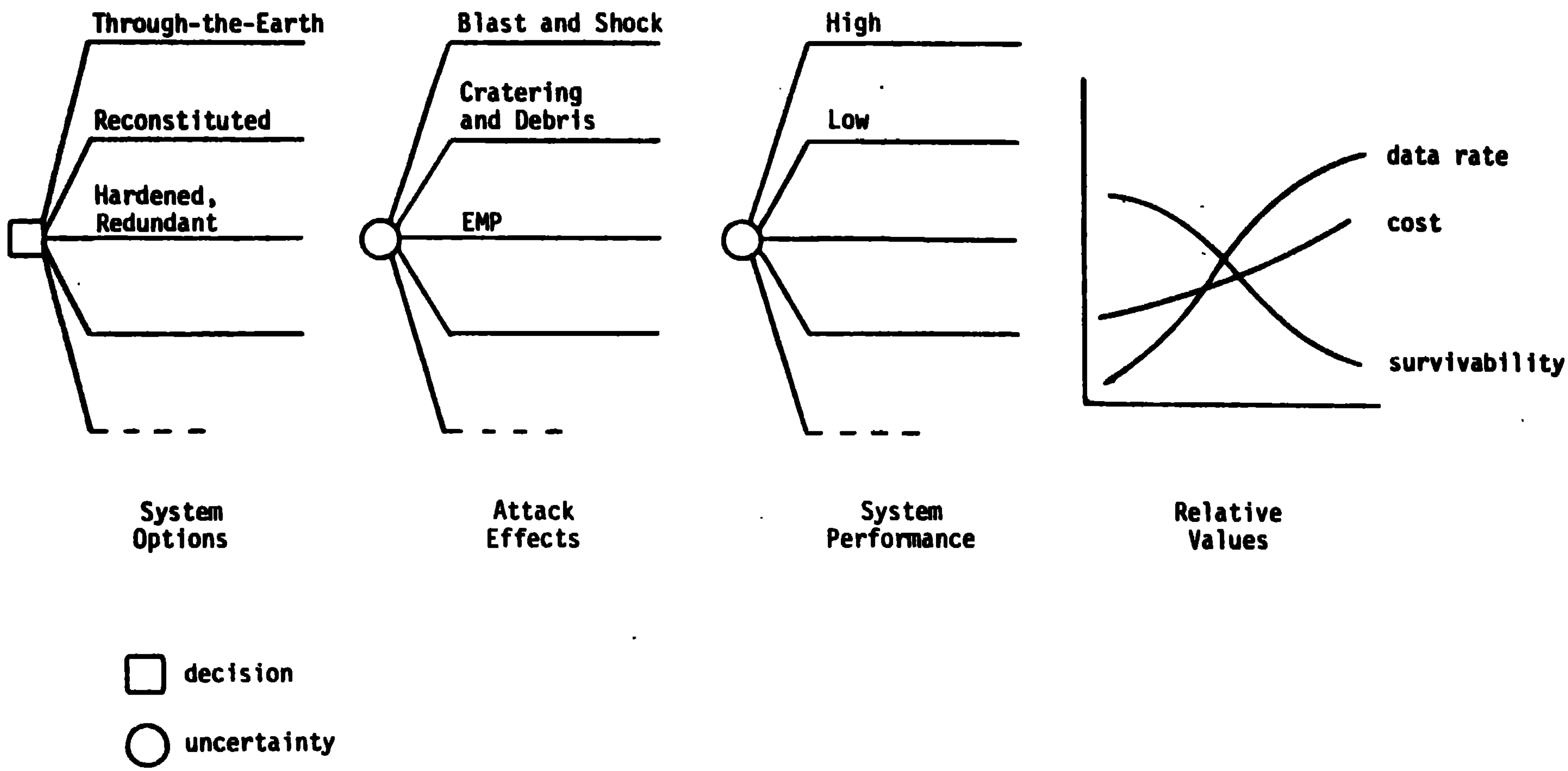

Figure 2-1. The deep base communications system performance is a function of the system option and the effects of the nuclear attack.

framework will focus on the subsurface to surface and surface to subsurface link needs of an ICBM DB plan.

The most important factor influencing the system choice is the effects resultant from a nuclear attack. The Soviet attack can be broken down into four components: (1) the effect of a single warhead detonating in the basing vicinity, (2) the effect of multiple warheads arriving and detonating near the target, (3) the probability that a warhead arrives and detonates at the target, and (4) the probability that a warhead survives fratricide to detonate. In constructing the decision methodology, we will focus on the first one, the effect of a single warhead. As the threat and its effects become further defined (refer to TRW document, 1985), the effects of multiple warheads will be the subject of future A.F. efforts. The third and fourth components are considered outside the scope of this analysis. The effects of a single warhead included in the model are blast and shock, cratering and debris, electromagnetic pulse, thermal effects, ionizing radiation, and effects on electromagnetic wave propagation.

The performance of the chosen communications system is a function of the alternatives chosen and the nuclear attack effects. The overall performance of the system comprises several measures including survivability, reliability, data rates, cost, compatibility, and power requirements. An overall measure of system performance requires an aggregation of these measures based on the relative values. Without such an aggregation there is no single index by which preference for options are expressed.

MODEL STRUCTURE

The initial decision analysis model consists of two sets of submodels, as shown in Fig. 2-2. The first set calculates the effects of a single warhead attack using nuclear weapons effects models. These effects are limited to those considered important to deep base communications system performance. Separate submodels are included for each of the nuclear effects mentioned above and are presented in Section IV of this report.

System performance is modeled by the second set of submodels using the attack effects and the communications system option as inputs. The system

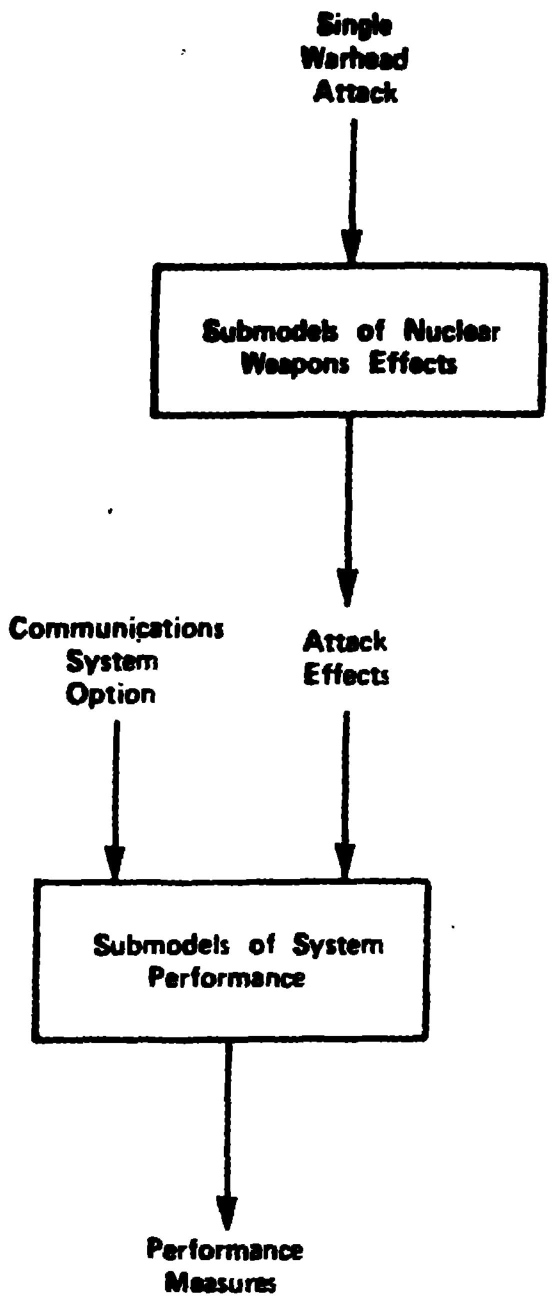

Figure 2-2. The initial decision analysis model consists of two sets of submodels and calculates the system performance measures based on a single warhead attack and the system option.

performance is expressed in terms of quantitative performance measures of the degree to which a system achieves the desired levels of reliable post-attack communications. The performance measures calculations are discussed in Section III of this report. The communications systems options themselves are covered in Section V.

The simple diagram in Fig. 2-2 will be expanded in detail following the discussions in Sections III, IV, and V. The expanded diagram illustrates each individual submodel and is included in this report as Fig. 6-1.

III. PERFORMANCE MEASURES

INTRODUCTION

To evaluate a deep base communication system, it is necessary to develop quantitative measures that reflect the degree to which a system's performance achieves the desired goals. If the performance measures are selected properly, then demonstrating that a given change in a communication system increases the values of the performance measures will be sufficient to show that the change represents a system improvement.

A key consideration in selecting quantitative performance measures is to ensure that they represent the communication goals as completely as possible. Another selection criterion is that the performance measures be readily assessable or quantifiable, preferably from existing data. A third consideration is that the measures be easily understood. Since a primary purpose of the evaluation framework is to help make decisions regarding communications systems, it is important that decision makers have intuitive understanding of the chosen measures.

The performance measures we have identified specify a communication system's performance in terms of the desired goals. The performance measures are survivability, reliability, compatibility, restoration time, data receive rate and data transmit rate. Power requirements and cost are two important communication system measures not directly related to performance that must be weighed into a final utility analysis. Each measure will be discussed below in terms of importance to meeting communication goals and the progress to date in quantifying each measure.

SURVIVABILITY

One of the most important concerns about deep base communications systems is their ability to survive a nuclear attack. This requirement applies not only to hardened systems that are also used for prestrike communications, but also to those systems intended to reconstitute communications (e.g., bore-out antennas). For reconstituted systems, the probability that the system will reconstitute communications given it survives the attack is also included in this performance measure. For our decision analysis, this means that we make comparisons between values for each effect of the nuclear weapons attack (blast, shock, etc., as described in Section IV) and the corresponding degree of resistance the system has to that effect. Because of the uncertainties in weapons effects and potential damage thresholds, the survivability measures will be probabilistic and expressed as probabilities of survival for different attack scenarios.

RELIABILITY

Given that the deep base facility communication system has survived the Soviet nuclear attack, there still remains uncertainty whether the system will receive the necessary message. This uncertainty is a function of the overall operating noise (including residual EMP effects). This noise originates from several noise sources at the receiving terminal of the system, including both internal and external sources.

This uncertainty about message reception given system survival is represented by a reliability performance measure and is expressed as the probability of message reception after a given number of trials. Details of the calculation of this probability are illustrated in Appendix 1 along with an example calculation.

COMPATIBILITY

Compatibility is a performance measure that expresses the degree to which a deep base communication system can communicate with existing military communication systems. Any deep base communication system may be required to interface directly with one or more of the following military communication systems*:

World Wide Military Communication System (WWMCS)
Primary Alert System (PAS)
HF Radio System
VHF Radio System
Strategic Air Command Control System (SACCS)

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* A synopsis of each of the listed military communication systems can be found in Appendix 3.

Strategic Air Command Digital Information Network (SACDIN)

AF Satellite Communication System (AFSATCOM)

Military Satellite (MILSTAR)

Ground Wave Emergency Network (GWEN)

The degree to which the given deep base communication system interfaces with the desired military communication system(s) will constitute a numerical score. This numerical score will be based on expert judgment. Judgment will be given on how complex the communications interface would be and to what degree either system's performance would be compromised in establishing interfaces.

We are not yet at the stage of identifying the military communications systems that each deep base communication option would have to communicate with. Furthermore, information necessary in this identification process includes requirements for deep base communication data rates. As a starting point, we are assuming that the C^3 requirements will be that of the Minute Man III (deFaye, 1985).

RESTORATION TIME

Restoration time is a performance measure that quantifies the time it takes to re-establish communication with the higher authority after a nuclear attack. Ideally, one would desire to have communications re-established immediately after an attack, that is, a restoration time of zero. For some communication options this is nearly the case, but for other options, in particular, for reconstitution methods such as the RBO and pop-up antenna options, significant restoration times may be required. For these communication options, minimizing restoration time is a very important driving force in the communication system design. Our initial assumptions for restoration time criteria will be based on Air Force suggestions as of the time of this analysis.

DATA RECEIVE RATE

Data receive rate is a performance measure of the rate (in bits/second) that a message from the higher authority can be received in the deep base. The data rate at which a message from the higher authority is sent must be commensurate with the required signal-to-noise ratio needed at the receiver. The data receive rate represents an undesired delay in message communication. This total delay is minimized for each communication option by maximizing the transmission rate.

DATA TRANSMIT RATE

Data transmit rate is a performance measure of the rate (in bits/second) that a message can be transmitted from the deep base to the higher authority. This rate must be commensurate with the signal-to-noise ratio required at the higher authority receiver. For some communication options (e.g., through-the-earth), the data transmit and data receive rate are probably different. Furthermore, the weight, or importance, of the rate at which a deep base can receive a message is not necessarily equal to the importance of the rate at which it can transmit a message.

POWER REQUIREMENTS

The power required to re-establish and maintain communication in a post-attack environment is an important attribute of a communication system. Power requirements are broken into two categories: power needed to re-establish a communication link and power needed to communicate messages to the higher authority. The power needed to communicate messages is further broken down into the power needed to transmit a message and the power needed to receive a message.

COST

Cost, expressed in present value dollars, is a measure of all communication options. Costs fall into four categories: development, installation, operating, and maintenance.

PERFORMANCE MEASURE AGGREGATION

The deep base communications decision problem involves several conflicting performance measures and attributes, for example, survivability versus data rate, or reliability versus cost. These conflicts make it very difficult to determine the preferred communications system. One approach to this difficulty is to structure the trade offs systematically between the conflicting measures. By explicitly formalizing a value structure, it is possible to weigh the importance of each measure to arrive at a weighted aggregate score for each communication system.

At this stage of the modeling effort, such a weighted aggregate of the performance measures is not required to gain basic insights into the decision problem. In the future, the model will be enhanced to aggregate these seven individual performance measures into a single measure of utility for a deep base communication system. This would be done using a multi-attribute utility function reflecting the decision-maker's tradeoffs among the different measures.

IV. NUCLEAR WEAPONS EFFECTS

NUCLEAR ATTACK

The ability of a deep base communications system to withstand a Soviet nuclear attack is directly dependent on the resulting effects. In our initial model, the nuclear weapons attack will be characterized as a single warhead detonation. To quantify the effect of a single warhead requires a two step process. First, the nature of the warhead itself must be specified. To keep the model clear and simple, the warhead is specified by three variables:

- o Yield (megatons)
- o Height of burst (feet)
- o Lateral distance from the burst to the deep base facility (feet)

When the attack is characterized as a single warhead in the above manner, the model can then calculate the effect on a communications system from the attack. The following effects resultant from a single warhead detonation are to be part of the model:

- o Blast and shock
- o Cratering and debris
- o Electromagnetic pulse (EMP)
- o Thermal effects
- o Ionizing radiation
- o Effects on EM propagation

In addition, some consideration must be given to:

- o Jamming

We will discuss each of these effects and various aspects of survivability and/or reliability of typical communication systems elements for each nuclear weapons effect.

It is emphasized that this report is not intended to provide a comprehensive, state-of-the-art database for nuclear weapons but, rather, to illustrate how information from such a database would be used in the decision analysis procedure.

Blast and Shock

Blast and shock due to a nuclear burst is of concern both in the near field and in the far field. The effects in the near field are obvious. An assessment of damage to underground or far-field surface structures is strongly influenced by geology and hydrology. Although numerical models and experimental data exist for several geologic media, the overall phenomenology is not well defined for all rock types.

In addition to geology and hydrology, the nature of blast and shock effects also depend upon the height (or depth) of burst, the warhead yield, and range of the deep base from ground zero. In particular, should the threat scenario include earth penetrator weapons (EPW) then a larger fraction of the weapon's energy will be coupled into the ground than with an air burst, significantly increasing the radius of damage for underground structures.

Cratering and Debris

Surface or near-surface nuclear explosions will produce craters and attendant debris accumulation around the craters. These phenomena are important inputs because they can affect communication system reliability and survivability. For example, in a reconstituted system that bores out from the deep base to the surface, serious problems could result if the borehole intersects a crater, particularly on a steep slope. This situation would make it extremely difficult to position, stabilize, and accurately aim a SFH or EHF antenna. The possibility of earth debris motion (rock slides into the crater, for example) due to rain, etc., could also present serious problems to a system that was reconstituted within a crater. Also, for a proliferated hardened surface antenna, debris piled up around a crater could cover the antenna structure, thus reducing the signal (attenuation) and hence the reliability of communications.

Electromagnetic Pulse (EMP)

Although blast, shock, and related mechanical effects pose a severe threat to the deep base, the electrical and electronic systems must also be protected from source region and high altitude EMP generated in a pre- (as in lightning) and/or trans-attack situation.

Because the bulk of the critical electrical/electronic systems will be located underground, direct illumination of system elements will be attenuated by the earth. The usual HF-SHF hazards should be minimized although coupling of lower frequency EM to large structures may be a problem. However, there will be metallic links from the surface to the deep base which could carry induced EMP currents to critical subsystems and components. Such elements could be direct penetrators, such as power cables or coaxial cables from surface antennas down to various systems, or they could be considered indirect entries, such as ventillation/exhaust ducts that could be energized by EMP and reradiate a pulse to sensitive equipment within the deep base. Protection will have to be provided to sensitive components and subsystems.

It is emphasized that an enormous amount of work has been done on EMP effects since the early 1960's when EMP was recognized as a severe threat to electrical and electronic systems. This work has been directed to analyzing the generation and characteristics of EMP, testing and computer simulation to estimate system susceptibility, and to methods of protecting systems, particularly critical military systems, against the deleterious effects of EMP.

The major portion of the HEMP energy lies in the LF and MF bands of the spectrum, although there is sufficient energy in the HF band and, in special cases, the UHF band to also be of concern. These higher frequency signals are hazardous to solid state devices. Antennas designed to receive signals in the UHF and lower frequency bands can be expected to pick up HEMP energy. Every conductor with dimensions greater than a quarter wavelength ($\lambda/4$) of the highest significant HEMP frequency must be considered to be an antenna which collects HEMP energy. The HEMP energy, as mentioned above, can be coupled to susceptible components, resulting in permanent damage and/or functional impairment. The main problem is one of specifying protection for facilities, equipment, and associated components. Protection specifications and design practices must form a technically consistent set that reduces HEMP energy below a predetermined level (10 μJ, e.g.) that will prevent all damage and most disruptions.

An example of a typical approach to the problem of protecting large communication systems against EMP is discussed in Appendix 4. This example is based on work by the Defense Communication Agency, which will result in a handbook for use in protecting the Defense Switched Network (DSN) against high-altitude EMP (HEMP). It is included in this report to indicate a way in which the necessary EMP information can be obtained for inclusion in our decision analysis structure. In this regard, it is very similar to the procedures described for other threats to the deep base. That is, one determines values of the threat, compares them to upset or damage thresholds of the system elements threatened, and then determines estimates of survivability/reliability probabilities.

Surface burst EMP, in the deposition region (from 3 to 6 km radius from ground zero) is characterized by high electric and magnetic fields. The radial electric fields are on the order of 100 kV/m, while the azimuthal magnetic field will be several hundred gauss (Sherman et al., 1975). The source region EMP contains very strong fields and may constitute a more dangerous hazard to a deep base. For distances greater than about 6 km, the radiated electric field can be estimated by

$$|E| \approx \frac{10^7}{d} \text{ Volts/meter} \quad , \quad (d \geq 6 \times 10^3 \text{ m}) \quad .$$

In conclusion, both surface burst and high altitude EMP constitute a threat to deep base communications. Because of the proximity of the source to the deep base and potential EMP links, the surface burst EMP poses the greater hazard. Adequate evaluation of this threat may require a detailed analysis of the final structure of the deep base and its communication links to the surface. However, a large amount of data is available to make an initial assessment of this threat for a generalized base configuration.

Thermal Effects

An enormous amount of energy per unit mass is released in a nuclear explosion, thereby producing very high temperatures (several tens of millions degrees centigrade). Because of these high temperatures, a significant percentage (70 to 80 percent in some cases) of the total energy (prompt) is released in the form of electromagnetic energy of short wavelength. Initially, the primary thermal radiations are mainly in the soft x-ray region of the spectrum but, for nuclear bursts below 50 miles in altitude, the x-rays are absorbed in the atmosphere in the general vicinity of the explosion. The atmosphere is in turn heated to high temperatures. Most of the remaining 20 or so percent of the energy is initially in the form of kinetic energy of the weapon debris. This energy is also absorbed by the air at a slightly later time and serves to further heat the air. This heated air, which constitutes the fireball, in turn radiates in a spectral region roughly similar to that of sunlight near the earth's surface. It is the radiation (ultraviolet, visible, and infrared) from the fireball, traveling with the velocity of light, which constitutes the thermal radiation at distances from the explosion.

The decision analysis structure requires the comparison of expected thermal levels and the damage thresholds of susceptible system elements. For example, if the most susceptible component is an insulated electrical cable whose insulation will melt at approximately 74 cal/cm^2, we must determine the conditions under which this level may be expected.

Ionizing Radiation

Prompt gamma rays and neutrons generated by a nuclear explosion can affect electronic equipment and cables, particularly fiber optics. Even though there may be little risk to the electronic components of the deep base communications system from nuclear radiation, there may be special conditions under which the components might become vulnerable. This section is therefore included to illustrate these risks in the kind of environment in which the system must function. In addition, obvious vulnerable configurations can also be identified and avoided in the development of the communications system.

Effects on Electromagnetic Wave Propagation

We can anticipate a large portion of the atmosphere to be ionized in the post-attack environment. Electromagnetic wave propagation will be affected, but the duration is not well defined. The nature of the effects are a function of frequency and mode of propagation and, therefore, will impact the various communication options for the deep base in different manners and for different periods of time.

Jamming

Noise will pose problems for any communication system. Such interference can eminate from nearby friendly sources or can be intentionally produced by the enemy through "jamming." Systems that operate in the lower portion of the electromagnetic spectrum are more susceptible to jamming because of inherent propagation characteristics (ground-wave, for example). Essentially, a system that can usually provide adequate performance will have its signal-to-noise ratio reduced, thereby resulting in serious performance degradation.

In general, most military communication systems are designed under the assumption that the jamming will be "unintelligent"; that is, the jammer fills the transmission band uniformly to effectively reduce the SNR at the receiver. There are a number of ways in which this threat can be countered - frequency hopping, pseudo-random spread-spectrum, etc. We will not discuss these systems in detail; however, we will assume that any viable candidate system for the deep base will employ anti-jam techniques. Also, some of the techniques used for anti-jamming are effective in noisy environments, specifically as could be encountered in a post nuclear attack environment. We are aware of many of these techniques and will consider them in our estimates of reliability.

V. COMMUNICATIONS OPTIONS

INTRODUCTION

The purpose of this section is to discuss the communications options identified to date. We will discuss these options in terms of the basic concepts that have been identified; through-the-earth communication, reconstituted, and hardened surface antenna. It should be noted that many of the communication options are hybrids of these basic concepts. Hybrid systems will be categorized by the strategy which dominates them.

Through-the-Earth Communications

Through-the-earth communication consists of communication by radiant wave energy. These waves can be either electromagnetic or seismic; however, electromagnetic is by far the more viable means of accomplishing communication at an acceptable signal rate and level of confidence. Consequently, the through-the-earth communication options discussed here will concentrate on electromagnetic (EM) communication.

In its simplest form and for the conductivity profiles expected, transmission must occur at a low frequency (ELF/VLF band) if any signal is to be detected for realistic transmitter power levels. Special circumstances exist where higher frequency signals can be used. However, for our initial evaluation we will consider basic earth attenuation effects. We can expect the attenuation properties of the earth and the noise characteristic to limit the transmittal rates.

We have three distinct through-the-earth options currently identified. These options are direct, passive staging, and active staging. The direct through-the-earth option, depicted in Fig. 5-1, consists of ELF transmitter/receiver combinations at the deep base and aboard the command center. Communication is accomplished directly. This option has the advantage of being simple and requiring little maintenance, but does require powerful transmitters and has the lowest data transmittal rates because of attenuation factors and antenna design.

The passive staging option (see Fig. 5-2) consists of transmit/receive loop antennas buried at incremental depths from the surface with hard wire

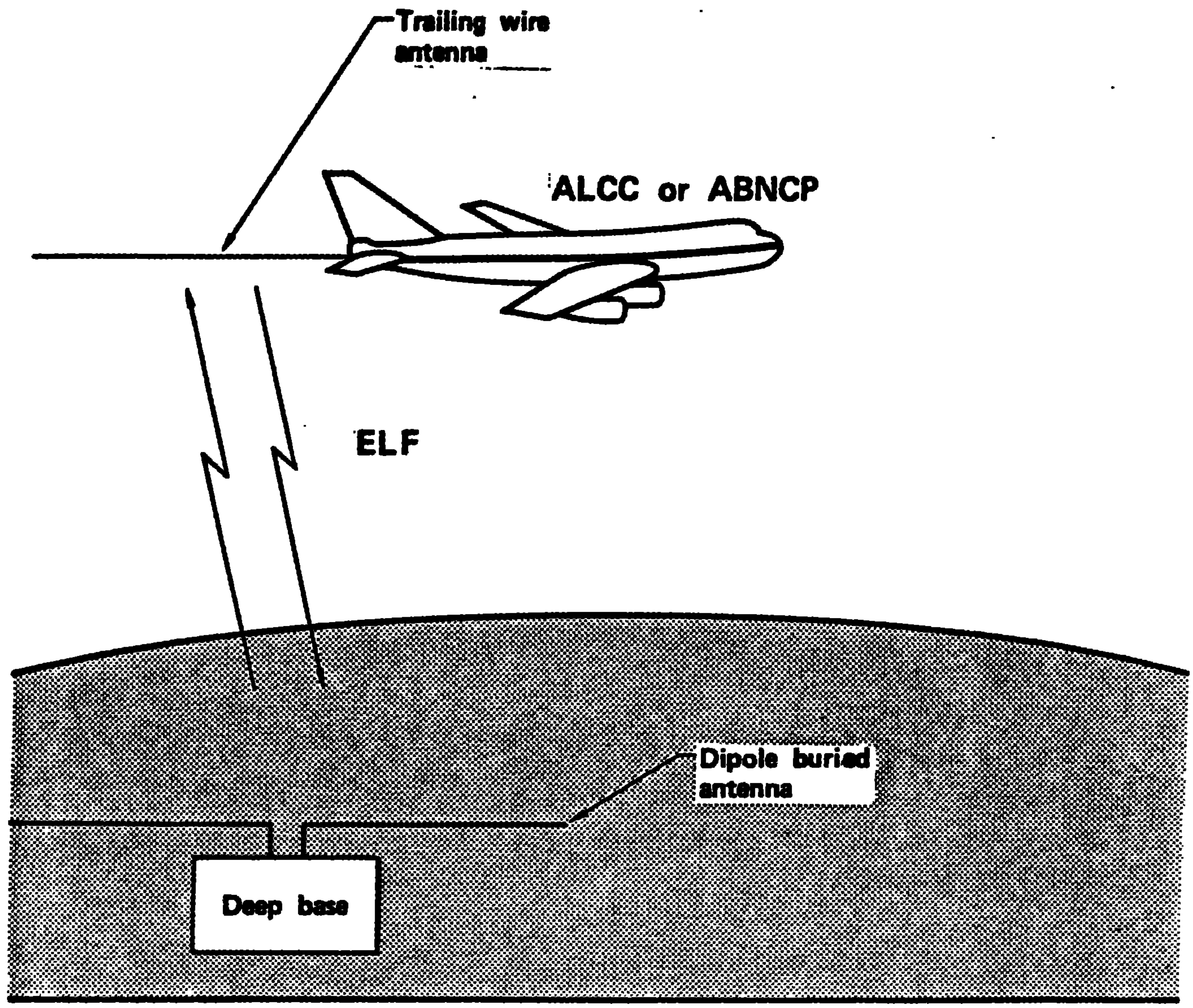

Figure 5-1. Direct through-the-earth ELF communications.

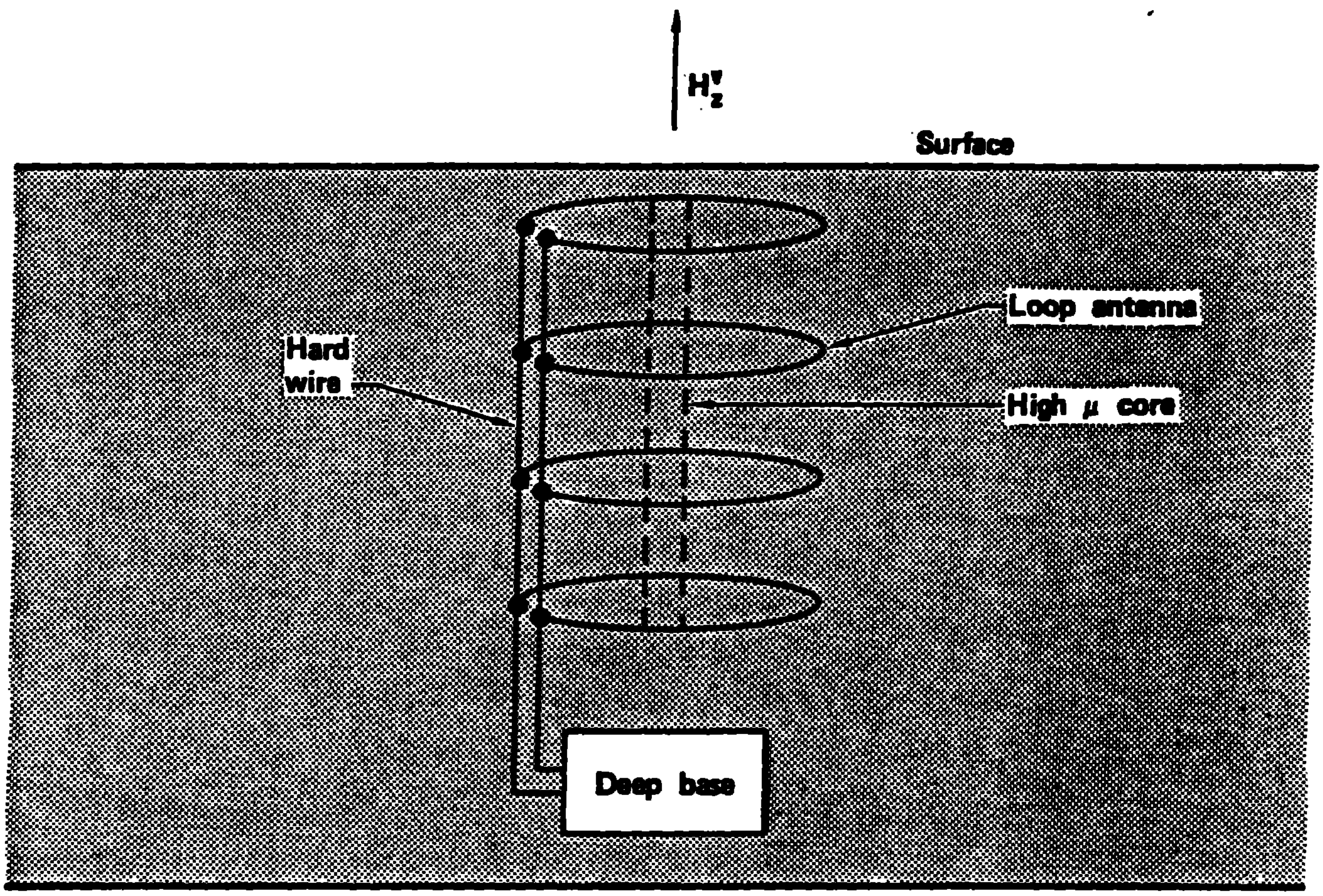

Figure 5-2. Multiple passive loops with hard wire.

links connected to the deep base transmitter/receiver. The loop antenna nearest the surface to survive the nuclear attack is then used for communication, thus minimizing the distance of communication through earth materials. This allows for the possibility of increasing information rate and/or increasing the signal-to-noise ratio at the receiver. However, because of its complexity, it has very high installation and maintenance costs.

The active staging option (see Fig. 5-3) consists of tiered transmitter/receiver units spaced incrementally from the deep base to near the surface. Each transponder will filter the received signal to increase the signal-to-noise ratio, then retransmit the message to be received by the next highest station. This approach has the advantage of significantly increasing the signal strength received at the surface and allows for higher information rates. It does, however, require power to be supplied to each transmitter/receiver station and is costly in installation and maintenance.

As noted earlier, there are ways of enhancing through-the-earth communications both in terms of signal-to-noise levels and in terms of information rate. These enhancements take advantage of wave guide phenomena and reradiation from conductors. Wave guides may exist in natural geological formations such as slant bedding planes or could be artificially created. Reradiation paths may exist in deep base construction or could be planned. In any case, these enhancements are not considered as separate options, but as specific design features of a given option.

Reconstituted Communications, RBO

Reconstituted communication systems are systems that restore a physical link, either wire or fiber optics, from the deep base to the surface. This allows for interfacing with several existing higher data-rate military communication systems depending on the antenna package and transmitter frequency band chosen. A special case of these reconstituted systems is the RBO option where a physical link is re-established by rapidly drilling to the surface. There are two basic reconstitution concepts identified at present: bore-out antennas (RBO as specific case) and pop-up antennas.

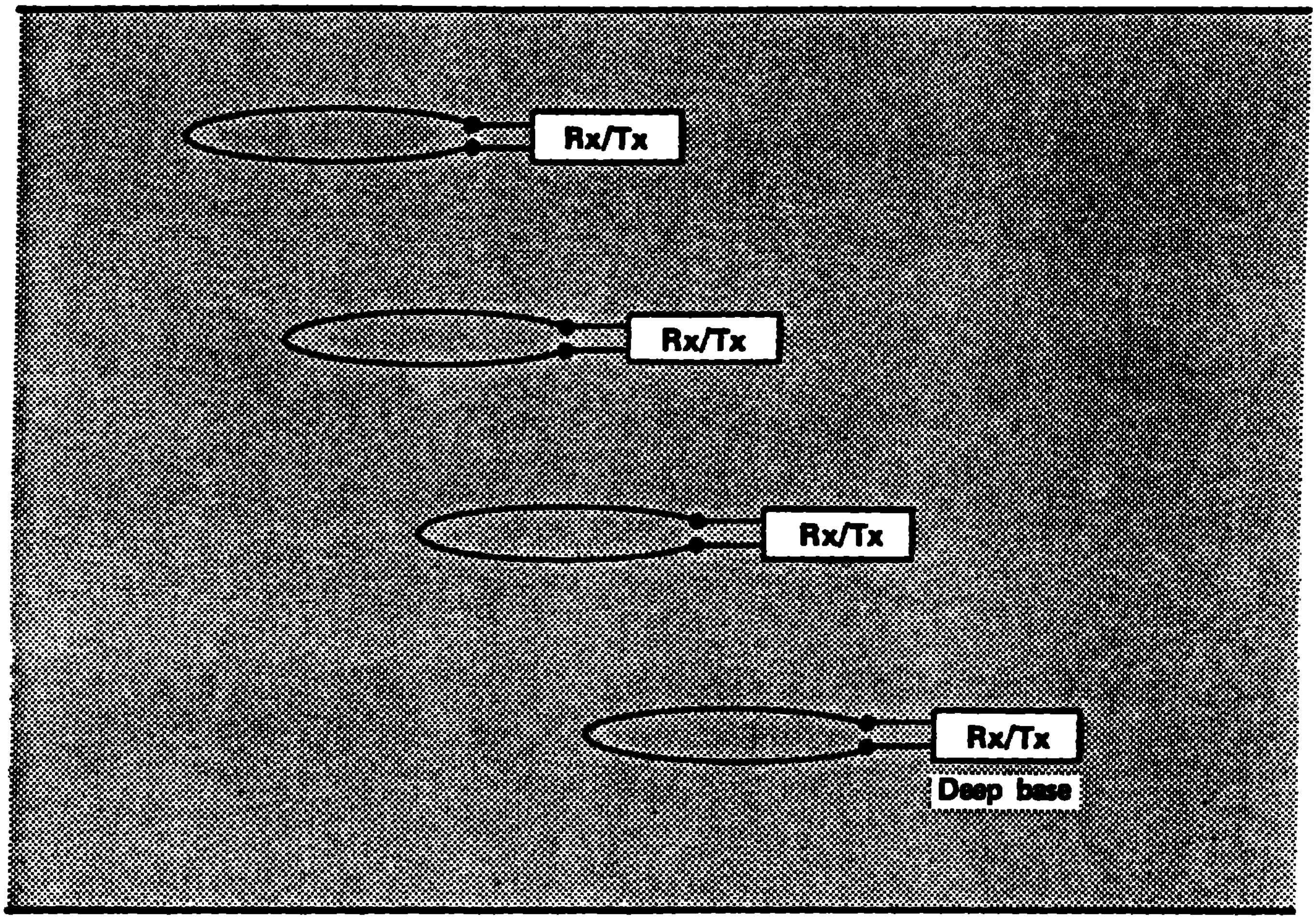

Figure 5-3. Multiple loops with receivers/transmitters.

Bore-out antennas (see Fig. 5-4) are hard-wire links that are reconstituted by a rig that drills a hole from the deep base to the surface. The hard wire and antenna package either ascends to the surface with the drill bit or is later pushed to the surface. This will be addressed in the next report.

Pop-up antennas consist of a pre-existing hole filled with a water and sand mixture and a buoyant antenna package with attached hard wire. This system floats to the surface when the need arises.

Dispersed Links and Hardened Surface Antennas

Although any communication option such as the bore-out antennas or through-the-earth, must contain multiple units and redundancy to give a high survival probability, extensive redundancy of hardened wire or fiber optic links between the deep base and the surface may prove equally survivable. This option (see Fig. 5-5) consists of multiple directionally drilled holes between the deep base and the surface that spread out to hardened antennas or communication link portals over a wide area. If the surface facility consisted of hardened surface antennas, then some would probably survive the attack. If the surface structures were portals, then some physical connection to an antenna or a direct link would have to be provided by an outside party.

Hybrid Links

Combinations of options, say through-the-earth EM propagation with proliferated hardened surface antenna, are possible. Also, the question of the system performance of the total communication system for the deep base would require analysis of multiple options--this too, is a hybrid link concept.

The proposed analysis procedure is applicable to these concepts, although it may be difficult to consider all of the permutations and combinations of communication options. Final analysis will strongly depend upon final base concept and communication requirements.

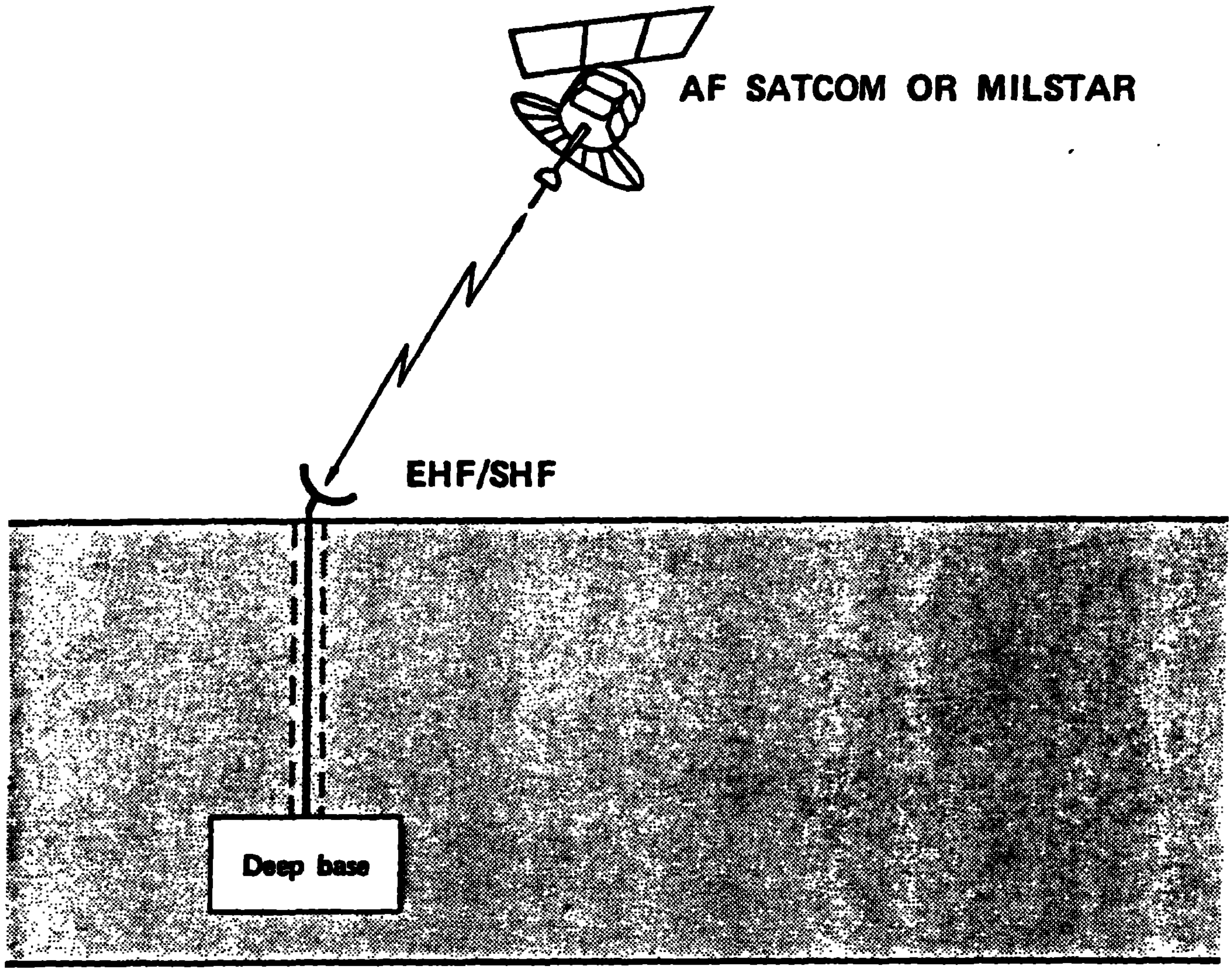

Figure 5-4. Bore-out antenna.

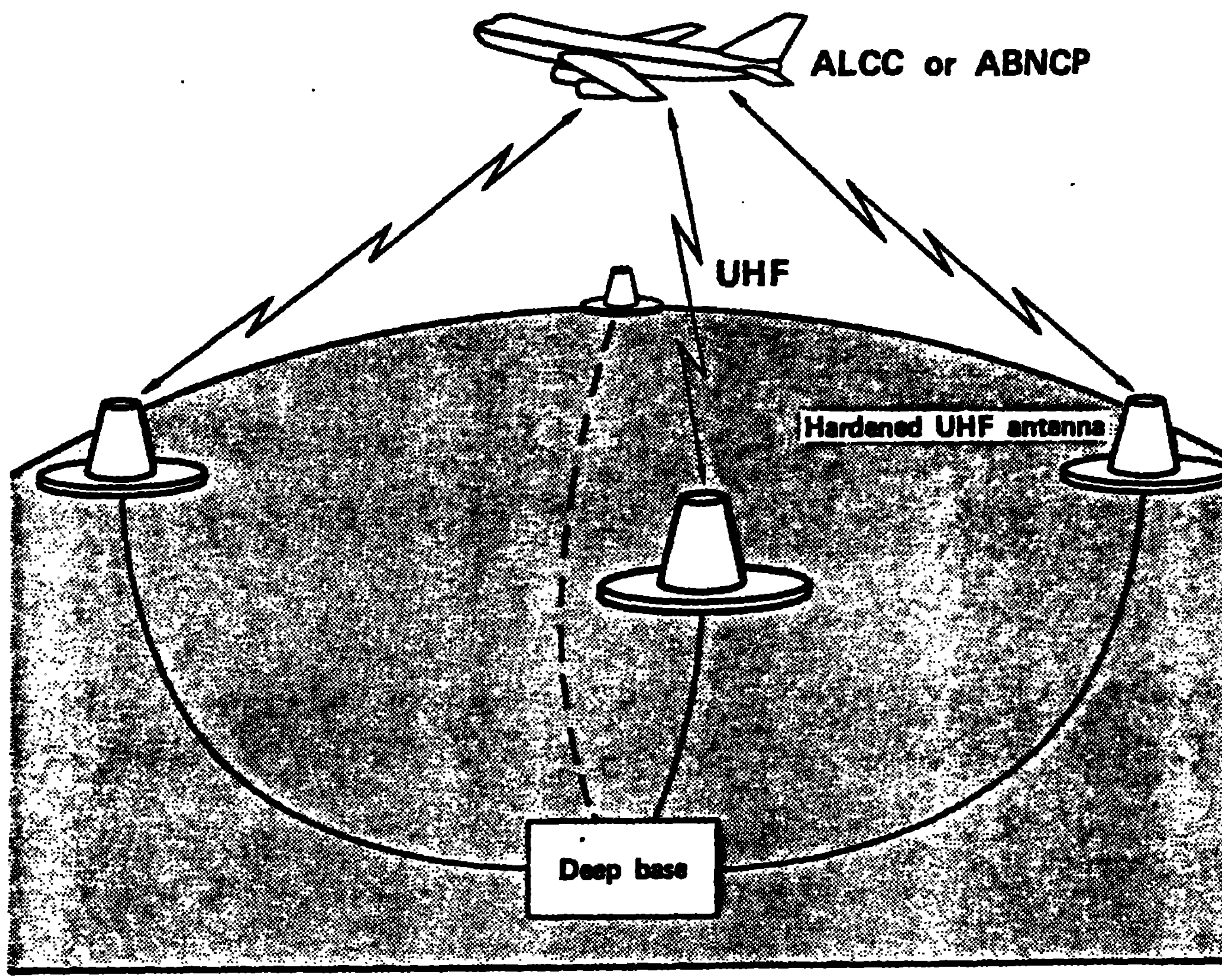

Figure 5-5. Dispersed hardened antennas with hard wire or fiber optics (or hybrid).

SYSTEM OPTIONS CHARACTERIZATION

The decision analysis model evaluates system performance by calculating system performance measures and attributes as a function of the attack effects and the design of the communications system option (recall Fig. 2-2). The submodels for calculating system performance require as input the nuclear attack effects expressed quantitatively as in Section IV (e.g., blast and shock as kbar of overpressure). These submodels also need a quantitative characterization of the communications option design.

An important step in characterizing the design of a system for evaluation is to specify the design of the deep basing facility itself. For purposes of the analysis, these factors are treated as given parameters and not as decision variables. They do, however, strongly influence the relative performance of different systems. There are two important parameters of the deep basing facility. The first and most obvious one is the basing depth in feet. The second is the geologic media of the basing location. The initial model being developed will consider only one type of geologic media, tuff, because of the proportionately greater amount of test data available for that medium. It is anticipated that future enhancements of the model will include an option for specifying a variety of geologic media.

A large number of factors are necessary to reflect the important aspects of each alternative communication systems design. Many of these factors are themselves performance measures, such as the data rates, power requirements, and compatibility criteria. Other factors relate to the system survivability and are generally expressed as the strength or hardness of the system against a particular nuclear attack effect (e.g., thermal hardening). Still other factors pertain to the system reliability (e.g., bit error rate, bandwidth, frequency, etc.). Also important are factors influencing time to restoration (e.g., bore-out rate) and those contributing to system cost (e.g., installation and operating costs).

Some of the design factors are more uncertain than others. Those that are known with a reasonable degree of certainty may be specified as a single value, others that are more uncertain must be expressed as probability distributions. The most uncertain of the design parameters are those relating to the survivability of the system.

As discussed previously, most of the communication systems under consideration consist of several different types of components. However, the current model evaluates each component separately. Future versions may be improved to consider combinations of different technologies.

VI. SUMMARY AND FUTURE EFFORTS

MODEL SUMMARY

The basic structure of the deep base decision analysis model was presented in Fig. 2-2. An expanded version of that figure is shown in Fig. 6-1. The figure reflects the discussion presented earlier on the nuclear weapons effects, the performance measures and attributes, and the communication options. Each of the boxes shown represents a separate submodel. The first row of boxes in the figure are the submodels used to calculate the effects of a nuclear attack. As presented in Section IV, in this model the nuclear attack is characterized as a single warhead and is specified by three variables: yield, height of burst (H.O.B.), and lateral distance. These variables, which are the inputs to the attack effects submodels, are shown on the top line of Fig. 6-1. The output of the attack effects submodels are the seven effects presented in Section IV, blast and shock, cratering and debris, etc.

The second set of submodels are the system performance submodels. One set of inputs to these submodels are the attack effects from the attack effects submodels. The other inputs are the factors characterizing the system option. These were presented in Section V and include some of the performance measures (e.g., data rates), system strength or hardness to nuclear attack effects and other factors related to reliability, cost, etc.

The overall outputs of the model and the outputs of the system performance submodels are the performance measures, such as survivability, reliability, cost, etc. The performance measures were discussed in Section III.

FUTURE EFFORTS

The next steps required in the development of this decision analysis model is to model the attack effects and performance measures, and to further characterize promising communications system options. Currently, the structure of our decision analysis model has been developed and substantial progress has been made in defining the performance measures. Until all the relationships among the threat, attack effects, and system performance are

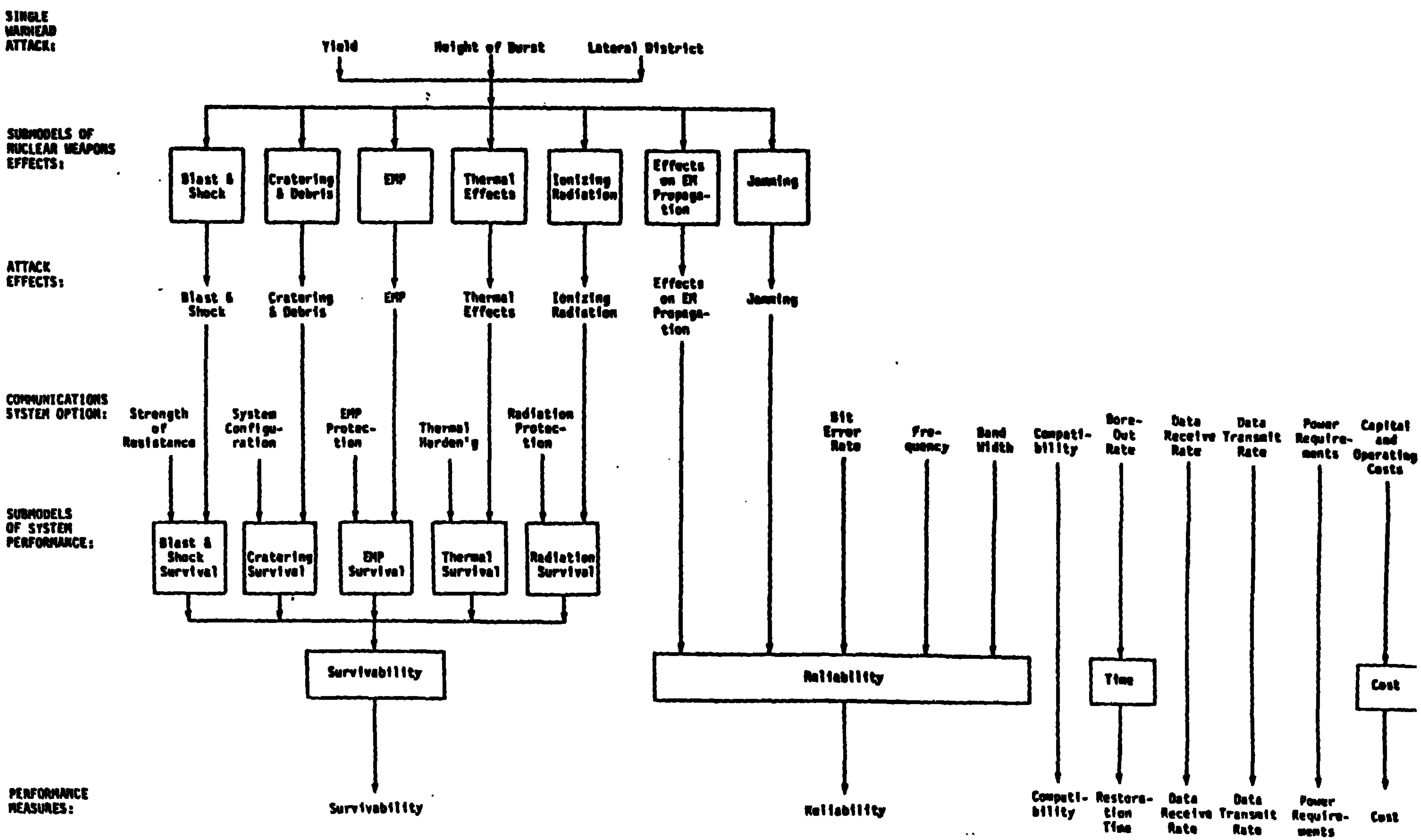

Figure 6-1. Detail structure of deep base decision analysis model.

modeled, however, the model cannot be used effectively to evaluate alternative communication options.

After all the important submodels in the decision analysis have been developed, a sensitivity analysis should be performed. This sensitivity analysis would provide insights into the model and the deep base communications problem through a review of the changes in the model outputs resulting from variations in inputs. Further modifications of the model could then be made.

One of the more significant results of this initial evaluation and sensitivity analysis discussed is an assessment of "value of information." This is a measure of the relative importance of additional research and data gathering about different nuclear attack effects or communications system designs. This information could then be used to prioritize future efforts in research and modeling.

While the initial model is under evaluation, several extensions to the model could be pursued. One of the first extensions to the model could be to develop a multi-attribute utility function. Using a relative weighting and combination of the performance measures, the multi-attribute utility function will provide a single measure of system performance.

A great deal more needs to be done. The data sets and submodels need to be operational for several different geologies. The importance of this model expansion depends on the variety of basing locations being considered. Performance measures for these new communications options must be defined. Finally, the model must be amended to consider multiple warhead attacks or specific attack scenarios. The success of this effort is highly dependent on the existence of reliable data on all aspects of C^3 problems.

As work progresses on characterizing promising system options, it may be necessary to evaluate systems which are combinations of very different technologies. At that point, new approaches to estimating performance measures such as reliability, survivability, etc. may be required.

ACKNOWLEDGMENTS

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APPENDIX 1
ANALYSIS OF COMMUNICATION SYSTEMS: ESTIMATES OF RELIABILITY

The main performance criterion for the Deep Base ICBM communication system is reliability. The performance measure for reliability, the probability of successfully receiving a desired message, takes into account that the system must not only operate in a noisy environment in which the noise itself is a random process, but also that the system is composed of subsystems and components having failure rates that are described statistically (mean-time-between-failure MTBF, for example). This probability will be denoted as $P_r\{m.s.|M\}$, which is the probability of correctly receiving at least one of M repeated messages. In our present treatment, we will assume that component failure is a much less likely effect than the degrading effects of noise and, therefore, will not consider component failure here.

Assume now that a message is composed of n bits, and that each bit is statistically independent of all others, and also that they all have a probability of error of $P_r\{\varepsilon\}$. For an error-free message, all n bits must be error free. In addition, we assume that the message is repeated M times. The probability of receiving at least one error-free message in M repetitions is

$$P_r\ \{m.s.|M\} = \left\{1 - \left[1 - (1 - P_r\{\varepsilon\})^n\right]^M\right\} \quad , \tag{1}$$

or, the allowable probability of bit error, given the required success probability, is

$$P_r\{\varepsilon\} = \left\{1 - \left[1 - (1 - P_r\{m.s.|M\})^{1/M}\right]^{1/n}\right\} \quad . \tag{2}$$

From the allowable value of bit error probability, we can determine the signal-to-noise ratio, SNR, the system must achieve (cf.: Sakrison, 1968). For comparison purposes, we will assume a simple binary-type PCM system with synchronous detection. We assume further that the decoder considers a pulse present when the instantaneous signal plus noise voltage exceeds some threshold level. Let the peak amplitude of the signal pulse be A_C, and choose the decision threshold as $A_{C/2}$. In addition, assume that we have used noise reduction and whitening techniques and, therefore, may consider the noise to be white and Gaussian. Thus,

$$P_r\{\varepsilon|_{\text{zero sent}}\} = P_r\{v > \frac{A_C}{2}\} = \int_{\frac{A_C}{2}}^{\infty} \frac{e^{-\frac{v^2}{2\sigma^2}}}{2\pi\sigma^2}\, dv \quad , \tag{3}$$

where v = noise voltage,

σ = rms voltage, around a zero mean

and

$$P_r\{\varepsilon|_{\text{one sent}}\} = P_r\{v < \frac{A_C}{2}\} = \int_{-\infty}^{\frac{A_C}{2}} \frac{e^{-\frac{(v-A_C)^2}{2\sigma^2}}}{2\pi\sigma^2}\, dv \quad , \tag{4}$$

which has the same value as (3). Thus, the probability of error is

$$P_r\{\varepsilon\} = \frac{1}{2}\left[1 - \text{erf}\left(\frac{A_C}{2\sqrt{2}\,\sigma}\right)\right] \quad , \tag{5}$$

where

$$\text{erf } x = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2}\, dy \tag{6}$$

This error probability as a function of SNR is shown in Figure 1, and represents the relationship we desired.

We now use the SNR, plus other system parameters, to determine the amount of transmitter power or magnetic dipole moment required to achieve that SNR. As an example, consider a through-the-earth EM propagation system which involves the ELF region of the spectrum. According to Mo (1975) and Raab (1984), up-links with receiving antennas near or above (airborne, e.g.) the earth's surface require more transmitter power to obtain the same SNR as down-links because of atmospheric noise. Although down-links will operate at higher receiving system temperature, their equivalent noise figures will be significantly less than those of the atmospheric noise-limited up-links. In other words, we could anticipate a different reliability performance measure for the receiver at the up-link as compared to the receiver at the down-link.

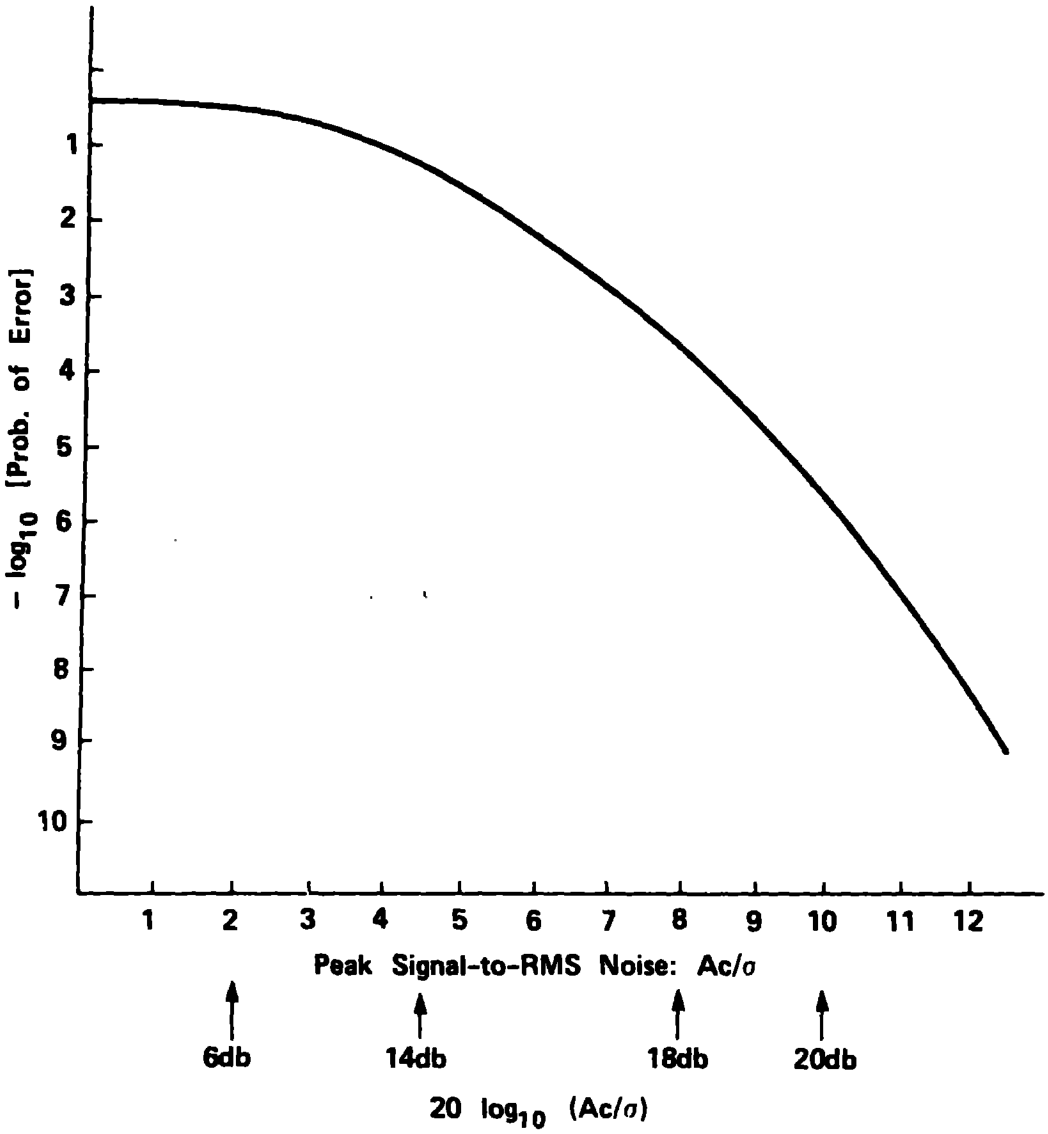

Figure 1. Error probability vs. signal-to-noise ratio.

Let's consider a simplified analysis of an up-link: transmission from a buried vertical magnetic dipole to the earth's surface where the receiving system is atmospheric noise limited. We wish to know the operating conditions where the probability, $P_r\{\epsilon\}$, for failing to receive at least one correct 75-bit message in thirty tries is one in a billion. In Eq. (2), m = 30 and n = 75. With Eqs. (3) through (6), we can derive a signal-to-noise ratio, SNR, of 16 dB. The computer code results (Buettner et al., 1985) from previous work can be used to determine the value of the magnetic field intensity produced by a vertical magnetic dipole located 762 meters (2500 feet) below the surface of the earth. Here, the propagation path is through a number of regions of different conductivities, as postulated in Generic Mountain C. This procedure yielded estimates of path loss and, coupled with the other factors in a power-budget equation (Eq. 7), permit us to estimate the required magnetic moment needed to achieve a specified SNR at the earth's surface.

The following relationship is used to estimate the necessary magnetic moment:

$$SNR = 20 \log_{10} \left(\frac{H_z^V \times NC \times CD \times \xi}{Hz_{AT} \times \sqrt{B}} \right) \qquad (7)$$

where

- SNR = Required Signal-To-Noise Ratio (dB) as determined from $P_r\{\epsilon\}$. SNR = 16 dB for our example.**
- H_z^V = Magnetic field intensity from a unit magnetic dipole moment.
- NC = The effect of noise cancellation, whitening, and other filtering. Assume 20 log NC = 40 dB.
- CD = The effect of additional coding on SNR. Assume 20 log CD = 6 dB.
- ξ = Required increase in magnetic moment to satisfy given SNR.
- H_{ZAT}^V = Value of atmospheric noise at the surface (normalized).

** This gives a probability of 1 in a billion of failing to correctly receive at least 1 75-bit message in 30 tries.

$\sqrt{B}$ = Square root of bandwidth - the normalization factor for the atmospheric noise.

The value of H_z^v at 2 kHz in Eq. (7) can be found from Fig. 2 (Buettner et al., 1985). From this,

$$20 \log H_z^v \approx -200 \text{ dB} > 377 \text{ A/m} \tag{8}$$

In terms of dB relative to 1 A/m,

$$20 \log H_z^v \approx -252 \text{ dB} > 1 \text{ A/m} \quad . \tag{9}$$

A plot of normalized atmospheric noise levels during the Summer in Colorado is shown in Fig. 3 (Maxwell and Stone, 1963). From this curve, the value for 20 log $\left(H_{ZAT}^v/\sqrt{B}\right)$ at 2 kHz is −37 dB > 1 μA/m-$\sqrt{B}$. For a bandwidth of 75 Hz, the value for the noise is

$$20 \log H_{ZAT}^v \approx -138 \text{ dB} > 1 \text{ A/m} \quad . \tag{10}$$

Using this, the values for the other terms in Eq. (7)--specifically, the values for "low σ's" in Fig. 2--we then have

$$20 \log \xi = 84 \quad , \tag{11}$$

where ξ is the magnetic moment of the transmitter. This indicates that to obtain the desired value of performance measure, the probability of one in a billion of failing for the specified message, then the underground source must be 84 dB > 1 A/m^2 at 2 kHz with a 75-Hz bandwidth.

From the above brief analysis, we can now determine the transmitter/antenna characteristics required for this system. It is emphasized that the above analysis is a very simplified one used to illustrate the basic approach used to determine pertinent data for the decision analysis structure. For example, the value of required magnetic moment, ξ, is dependent on the location of the transmitter and the geology. Also, air

		← receiver
1	σ=0.005-0.1 S/m	200′ thickness
2	σ=0.002-0.07 S/m	1000′
3	σ=0.10-1.0 S/m	750′
4	σ=0.05-0.2 S/m	150′
5	σ=0.01-0.04 S/m	1200′ ← source
6	σ=0.05-0.2 S/m	

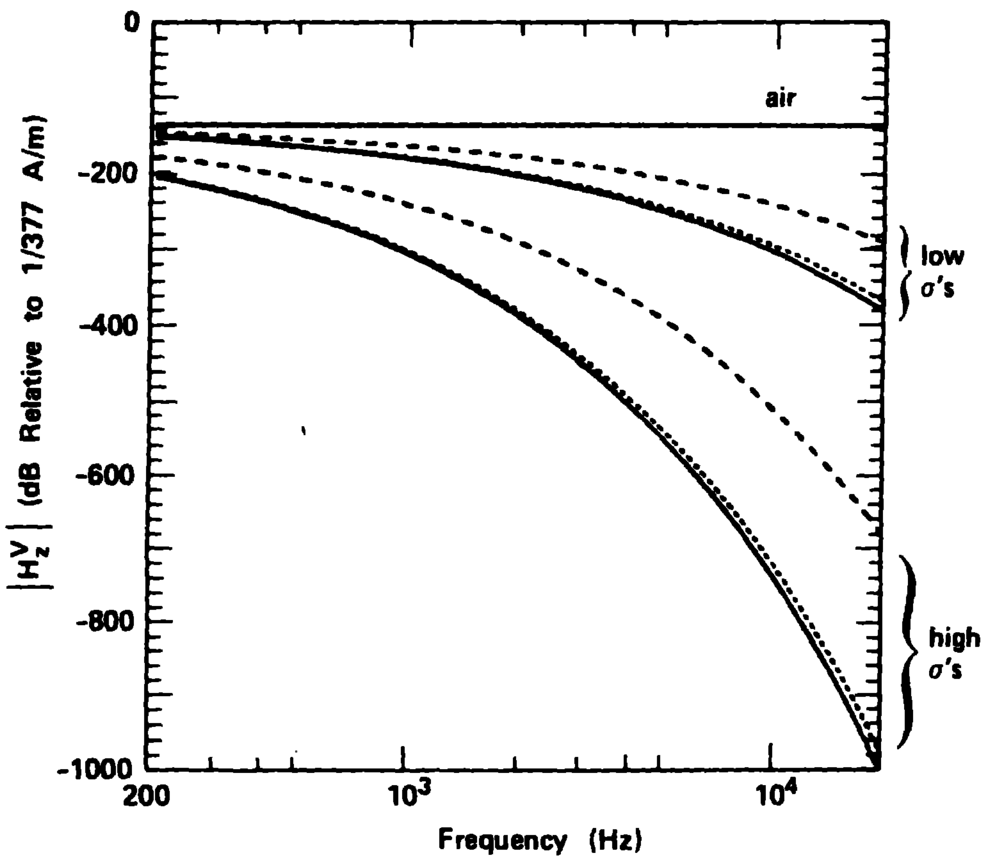

Figure 2. The vertical magnetic field is shown above a vertical magnetic dipole source at a depth of 2500 ft. in a stratified medium. Variations in layer thickness, as well as conductivities, were considered in the range from best to worst cases. Results included the model shown (————), depth of layer 4 = 0 (- - - - - - - - - - - -), and depths of layer 4 = 0 and layer 3 = 250′ (– – – – – – – – –). (from Buettner, et al., 1985, revision 1)

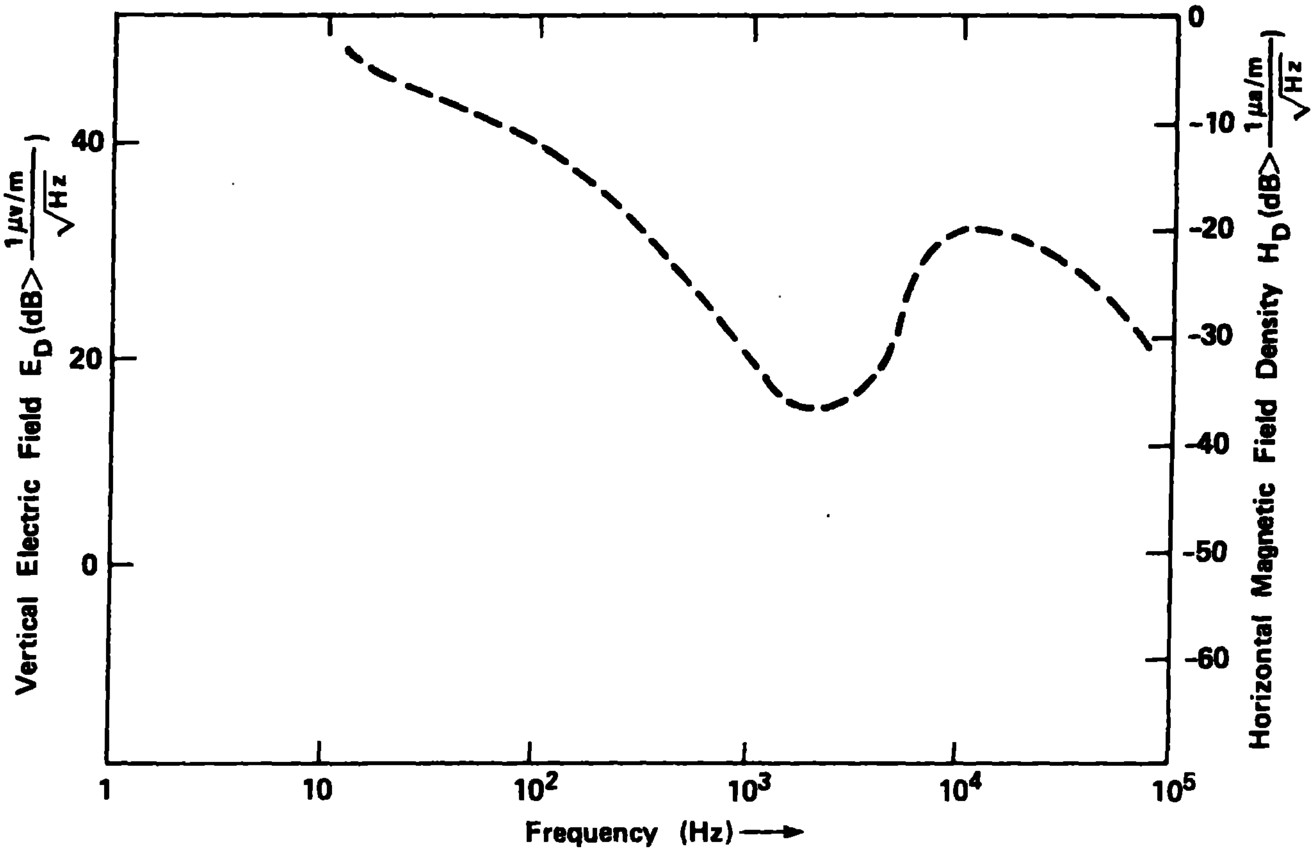

Figure 3. Natural noise density - Summer, 0800-1200, in Colorado (after Maxwell and Stone, 1963)

atmospheric noise has regional characteristics, local characteristics, and seasonal and diurnal changes--it is also site specific to some extent. A normalized* value of this attribute, "required magnetic moment," may better suit the decision analysis procedure. When multiplied by the weight of the attribute, it then becomes an input to the multi-attribute utility function in the decision analysis, discussed in Section III.

To illustrate the additional complexities involved in more accurate estimates of the performance of communication systems operating in an atmospheric noise environment, a further example is presented in Appendix 2.**

* For the actual decision analysis procedure, the value of ξ could be normalized by dividing the minimum value of required magnetic moment, ξ, by each of the other systems values: $V_i = \frac{\xi_{min}}{\xi_i}$, so that $\frac{\xi_{min}}{\xi_{max}} \leq V_i \leq 1$. (See Keeney and Raiffa, 1976, and Latorre and Spogen, 1982).

** Some question may arise as to the reason we are concerned with atmospheric noise since, for a significant time period after a nuclear attack, this noise will be greatly reduced (Glasstone and Dolan, 1977). The main reasons for our approach are, 1) the system must be tested, and that means it will have to operate in an atmospheric noise environment (pre-strike), and, 2), the system is to have a relatively long lifetime--well past the period in which the noise was low.

APPENDIX 2
ANALYSIS OF RELIABILITY OF ATMOSPHERIC RADIO NOISE-LIMITED COMMUNICATION SYSTEMS

In Appendix 1, we presented an example of the analysis of an ELF-VLF through-the-earth communication system. That example was considerably simplified, in that a number of assumptions about the atmospheric radio noise and the processing of it were made. The purpose of this Appendix is to provide a much more comprehensive method of analysis of reliability and to illustrate the procedure that will probably have to be used when more accurate results are required.

One of the most significant performance measures for a receiving system is the overall operating noise factor, f. This factor is composed of a number of noise sources at the receiving terminal of the system. It is necessary to consider both internal and external noise, referred to the input of the receiver (output terminals of a lossless antenna). For receivers free from spurious responses, the system noise factor (cf.: Martin, 1955) is given by

$$f = f_a + (\ell_c - 1)\left(\frac{t_c}{t_o}\right) + \ell_c(\ell_t - 1)\left(\frac{t_t}{t_o}\right) + \ell_c\ell_t(f_r - 1) \quad , \qquad (1)$$

where

f_a = the external noise factor defined as

$$f_a = \frac{p_n}{kt_o b} \quad , \qquad (2)$$

F_a = the external noise figure defined as $F_a = 10 \log f_a$,

p_n = the available noise power from a lossless antenna,

k = Boltzmann's constant = 1.3802×10^{-23} J/K,

t_o = the reference temperature in degrees K taken to be 288°K,

b = the noise power bandwidth of the receiving system in Hz,

ℓ_c = the antenna circuit loss $\left(\frac{\text{available input power}}{\text{available output power}}\right)$,

t_c = the actual temperature, in °K, of the antenna and nearby ground,

ℓ_t = the transmission line loss $\left(\frac{\text{available input power}}{\text{available output power}}\right)$,

t_t = the actual temperature, in °K, of the transmission line,

f_r = the noise factor of the receiver (F_r = 10 log f_r; the noise figure in dB).

If $t_c = t_t = t_o$, equation (1) becomes

$$f = f_a - 1 + f_c f_t f_r \quad , \tag{3}$$

where f_c is the noise factor associated with the antenna circuit losses:

$$f_c = 1 + (\ell_c - 1)\left(\frac{t_c}{t_o}\right) \quad , \tag{4}$$

and f_t is the noise factor associated with the transmission line losses:

$$f_t = 1 + (\ell_t - 1)\left(\frac{t_t}{t_o}\right) \quad . \tag{5}$$

Equation (2) can be written as

$$P_n = F_a + B - 204 \quad \text{dBW} \quad , \tag{6}$$

in which $P_n = 10 \log p_n$, $B = 10 \log b$, and $10 \log k\, t_o = -204$. For a short ($h \ll \lambda$) grounded vertical monopole, the vertical component of the r.m.s. field strength is given by:

$$E_n = F_a + 20 \log_{10} f_{MHz} + B - 95.5 \quad \text{dB} > 1\ \mu\text{v/m} \quad , \tag{7}$$

where E_n is the field strength in bandwidth b, and f_{MHz} is the center frequency in MHz. Similar expressions for E_n can be derived for other antennas. For example, for a half-wave dipole in free space,

$$E_n = F_a + 20 \log_{10} f_{MHz} + B - 99 \quad \text{dB} > 1\ \mu\text{v/m} \quad . \tag{8}$$

The external noise factor may also be expressed as a temperature, t_a, where, by definition of f_a,

$$f_a = \frac{t_a}{t_o} \quad , \tag{9}$$

t_o is the reference temperature in °K, and t_a is the antenna temperature due to external noise.

The preceding review of noise relationships in a receiving system is important in that it establishes some of the basic information required in the analysis. In addition, there are three definitions which will be used as well. They are:

1. <u>Grade of Service</u>

Grade of Service is a measure of the communication reliability evaluated over a relatively short time period (minutes to an hour) during which the statistics of the relevant performance parameters may be considered stationary. The Grade of Service could be expressed as a bit error probability, percentage of error-free messages, etc.

2. <u>Time Availability</u>

Time availability refers to the percentage of time that a given minimum Grade of Service is achieved. The period of time chosen for the definition will normally be influenced by the nature of the system variables.

3. <u>Service Probability</u>

Service probability may be defined as the probability that the specified Grade of Service or better will be achieved for the percentage of time corresponding to the time availability. The service probability expresses all the uncertainties or standard deviations as a single parameter and gives a measure of the confidence in the predicted system performance.

Essentially, there are four operations involved in performing the system analysis. First, the nature of the signal as it appears at the input to the detector must be determined. This will usually consist of calculations involving such items as the transmitter power, antenna gains, coupling and tuning losses, and the propagation path characteristics. Second, the nature of the noise or interference as it appears at the detector input must be determined. This will include evaluating the total power from sources external or internal to the receiving system. Third, a mathematical model for the detection system is required. Fourth, the expressions for the signal, noise, and detector model are manipulated to obtain an expression for the detector output in the desired form.

Depending upon the type of communication system desired, there are numerous variations in the actual details of the steps described above. There will be a few assumptions and idealizations necessary at the outset; therefore, the final performance predictions must be considered in that light.

For our example, we consider the following system requirements and conditions:

Frequency: 10 kHz

Modulation: FSK

Season: Summer

Time of Day: 2000-2400 hrs.

Bandwidth: 75 Hz

Propagation: Continuous wave (carrier)

Grade of Service: 0.01% binary errors/hr.

We want to access the probability that a given received signal power will provide the specified Grade of Service for any given percentage of the hour. The expected value of the received power, P_e, required for a particular Grade of Service during an hour when the antenna noise figure is F_a, is

$$P_e = F_a + R + B - 204 \quad (\mathrm{dBW}) \quad , \tag{10}$$

where R is the required signal-to-noise ratio for the given bandwidth B and 204 is derived from 20 log kT. If the receiving antenna is a short vertical rod, the corresponding field strength, E_e, is

$$E_e = P_e + 20 \log_{10} f_{MHz} + 108.5 \quad \mathrm{dB} > 1\ \mu v/m \quad . \tag{11}$$

The probability of a binary error in a narrow-band frequency modulation system is equal to one-half the probability that the noise envelope exceeds the carrier envelope at any instant. Therefore, to determine the required signal-to-noise ratio, we must find the noise amplitude probability distribution (APD). From Fig. 1 (Spaulding and Washburn, 1985), the value of V_{dm} (the expected value of the median deviation of the average voltage) at 10 kHz for 2000-2400 hours in the Summer is 9 dB (200 Hz bandwidth). Converting to a 75 Hz bandwidth (using Fig. 2) (Spaulding and Washburn, 1985), the resulting value of V_{dm} is 8 dB. The corresponding APD is then plotted (Fig. 3) (Spaulding and Washburn, 1985).

According to Montgomery (CCIR, 1963), the required Grade of Service implies that the noise envelope will exceed the carrier envelope 0.02% of the time. With the APD (Fig. 3) corresponding to 8 dB (75 Hz bandwidth); the carrier envelope must be approximately 26 dB above A_{rms}. Therefore, the value for R is 26 dB. The uncertainty in this value due to variations in the APD slope is approximately 1 dB (CCIR, 1963).

F_{am} is now used to determine F_a, and the deviation, D, which is consistent with the percentage of hours during which a satisfactory Grade of Service is obtained. As an example, the 1 MHz noise grade for the western United States may be located is 80 (Fig. 4) and the value of F_{am} at 10kHz is, therefore, 162 dB (Fig. 5), with a standard deviation $\sigma_{F_{am}}$ of 3.1 dB (Spaulding and Washburn, 1985). The probability that a given deviation, $D = F_a - F_{am}$, will occur allows for uncertainties in the value of the noise level, F_a, in a given hour. From Fig. 1, the value of D_u is 4.1 dB and from this, values of D are plotted on normal probability paper (Fig. 6) under the assumption that the distribution of the decibel values above the median is normal. Similarly, σ_{D_u} (1.1 dB) is determined and a curve for it plotted in Fig. 6 as well.

Returning to equation (9), P_e can be plotted (Fig. 7) by taking the percentage time availability as 100 minus the percentage of time that D is exceeded. For our example, $P_e = D + 2.8$; it is now necessary to consider the prediction uncertainties. This is done by considering the following standard deviations:

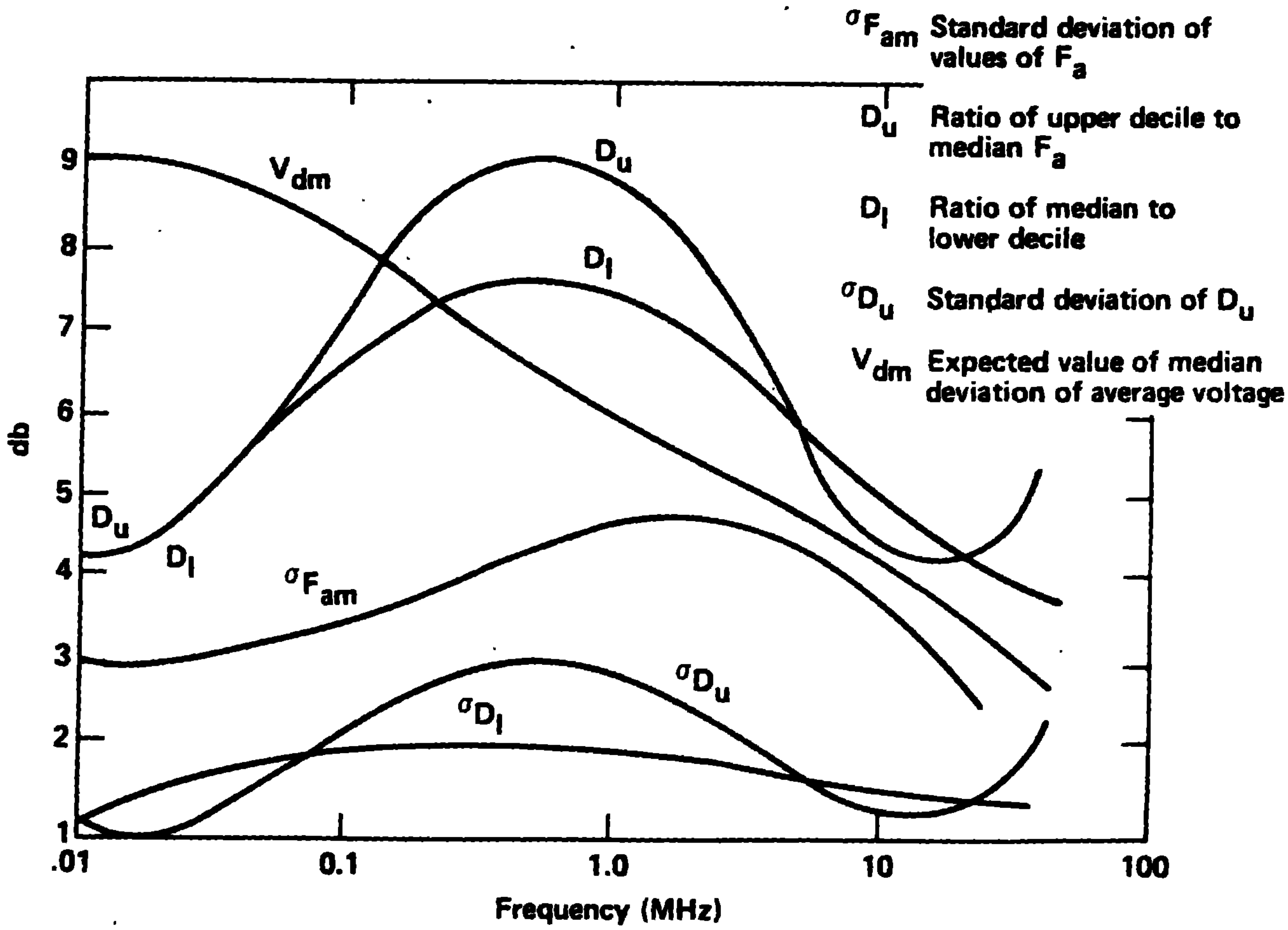

Figure 1 Data on noise variability and character (summer, 2000 - 2400 hrs. after Spaulding and Washburn, 1985)

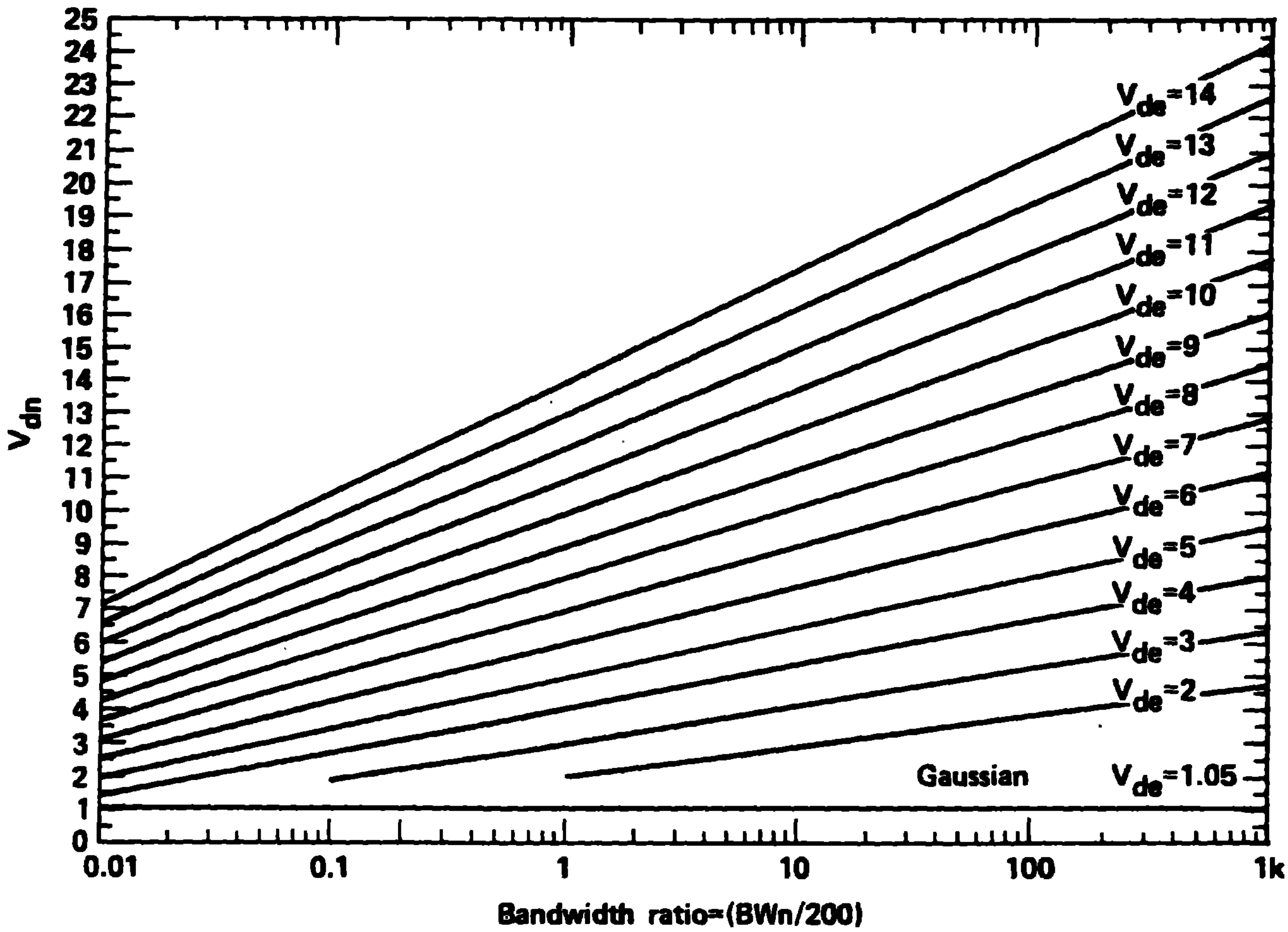

Figure 2 Translation of a 200-Hz bandwidth V_d, V_{de}, to other bandwidths, BWn. (after Spauldine and Washburn, 1985)

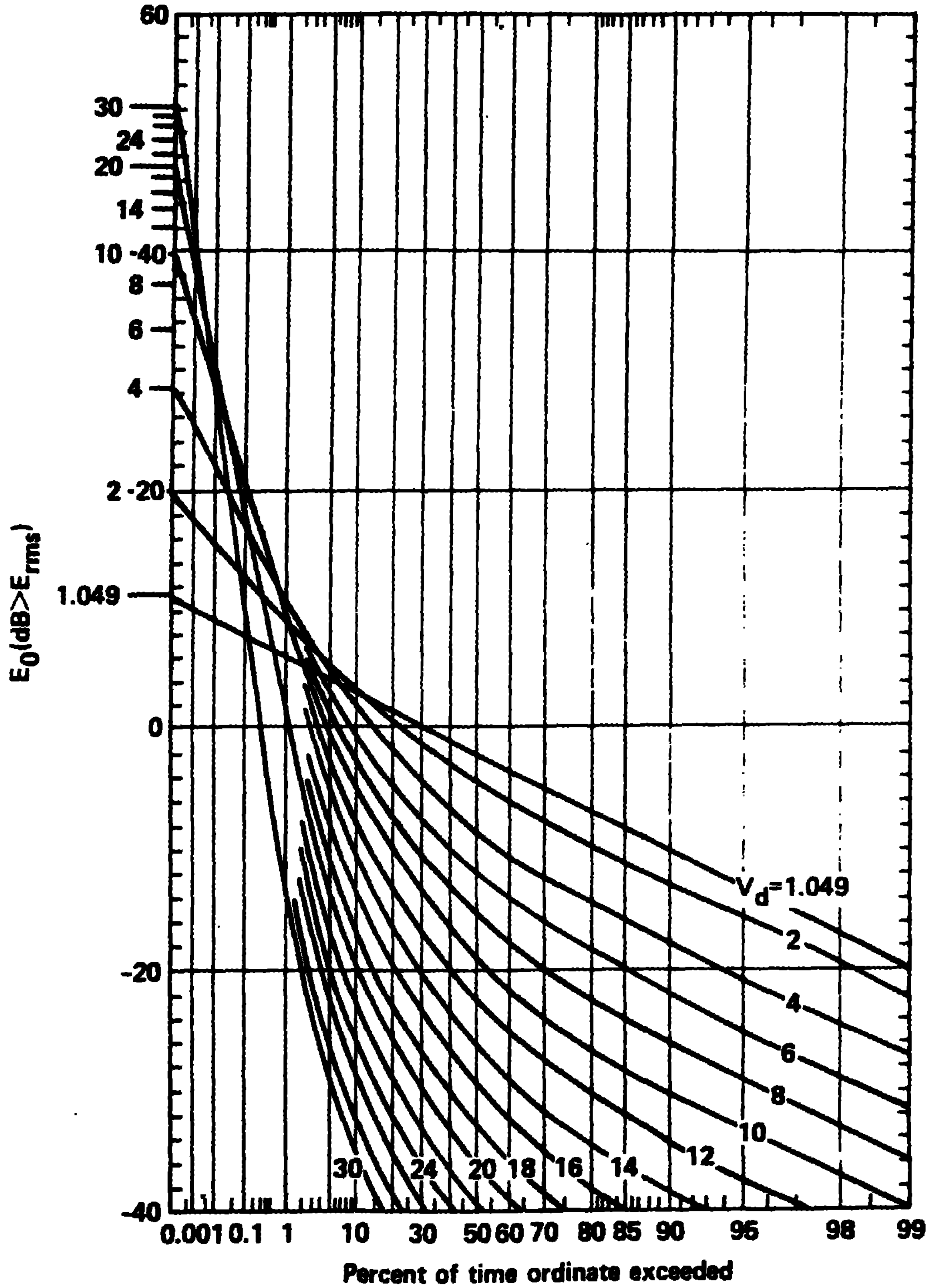

Figure 3 New set of amplitude probability distributions for atmospheric radio noise for various values of V_d. (after Spaulding and Washburn, 1985)

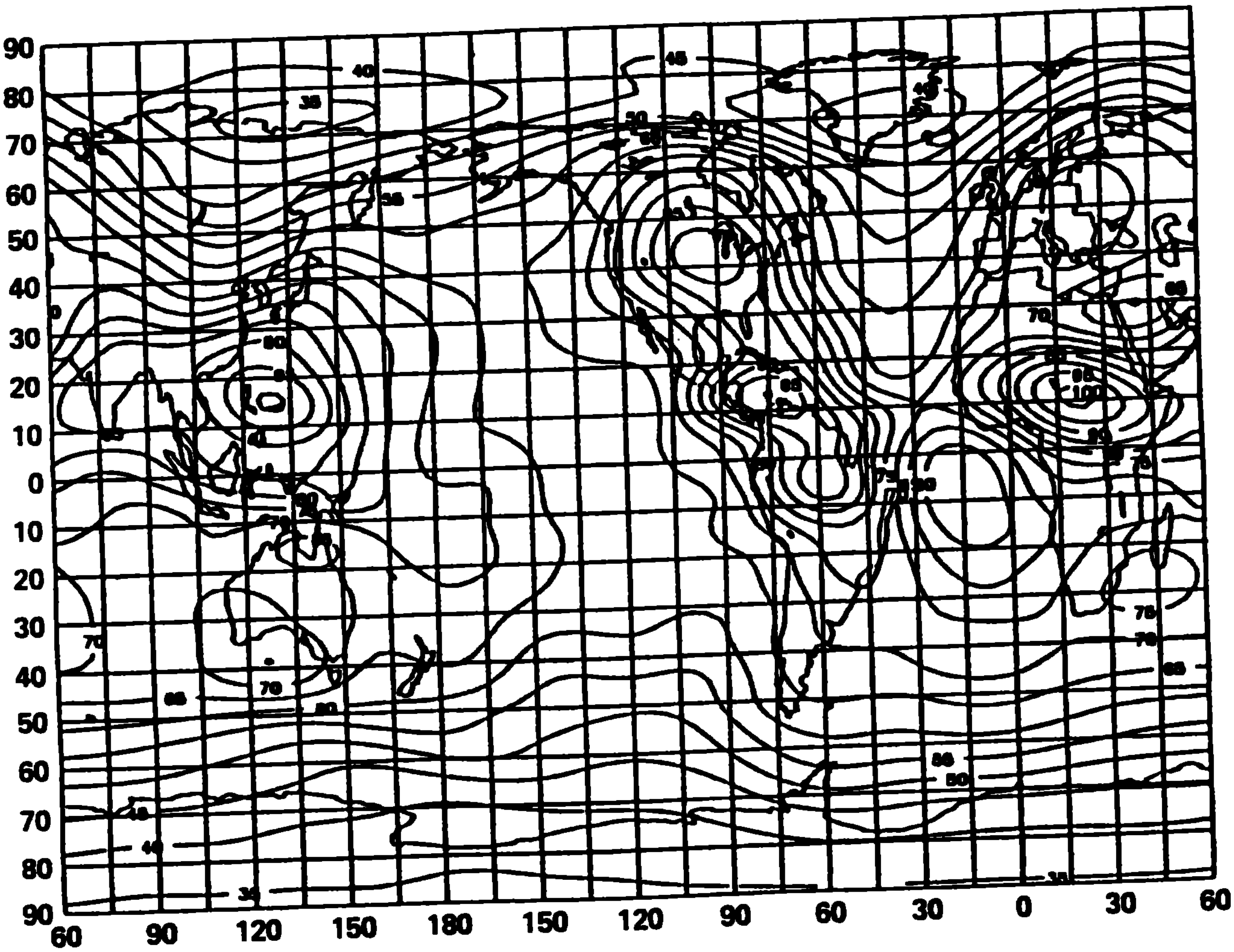

Figure 4 Expected values of atmospheric radio noise at 1 MHz, F_{am} (dB above kT_0b), for June, July, August, 2000-2400 hours. (after Spaulding and Washburn 1985)

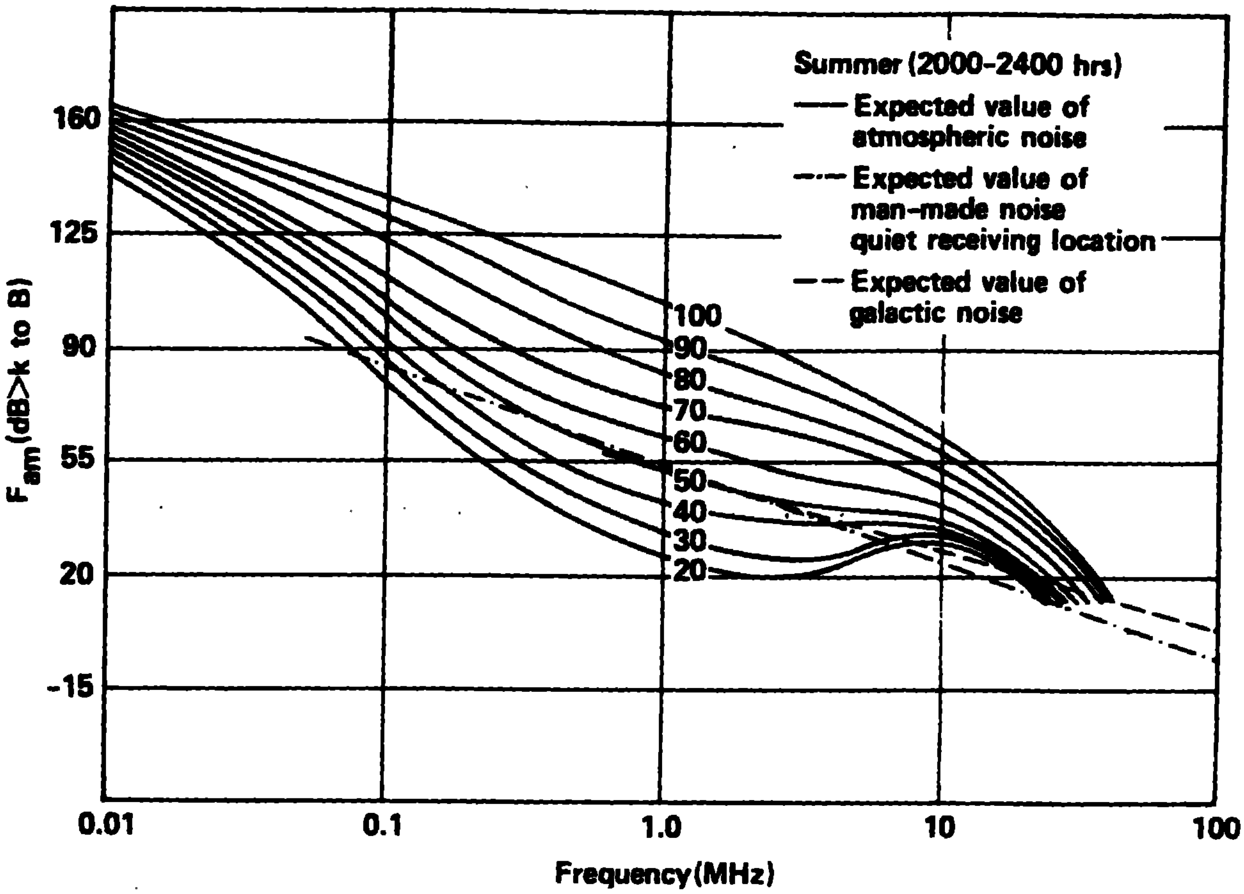

Figure 5 Variation of radio noise with frequency. (after Spaulding and Washburn, 1985)

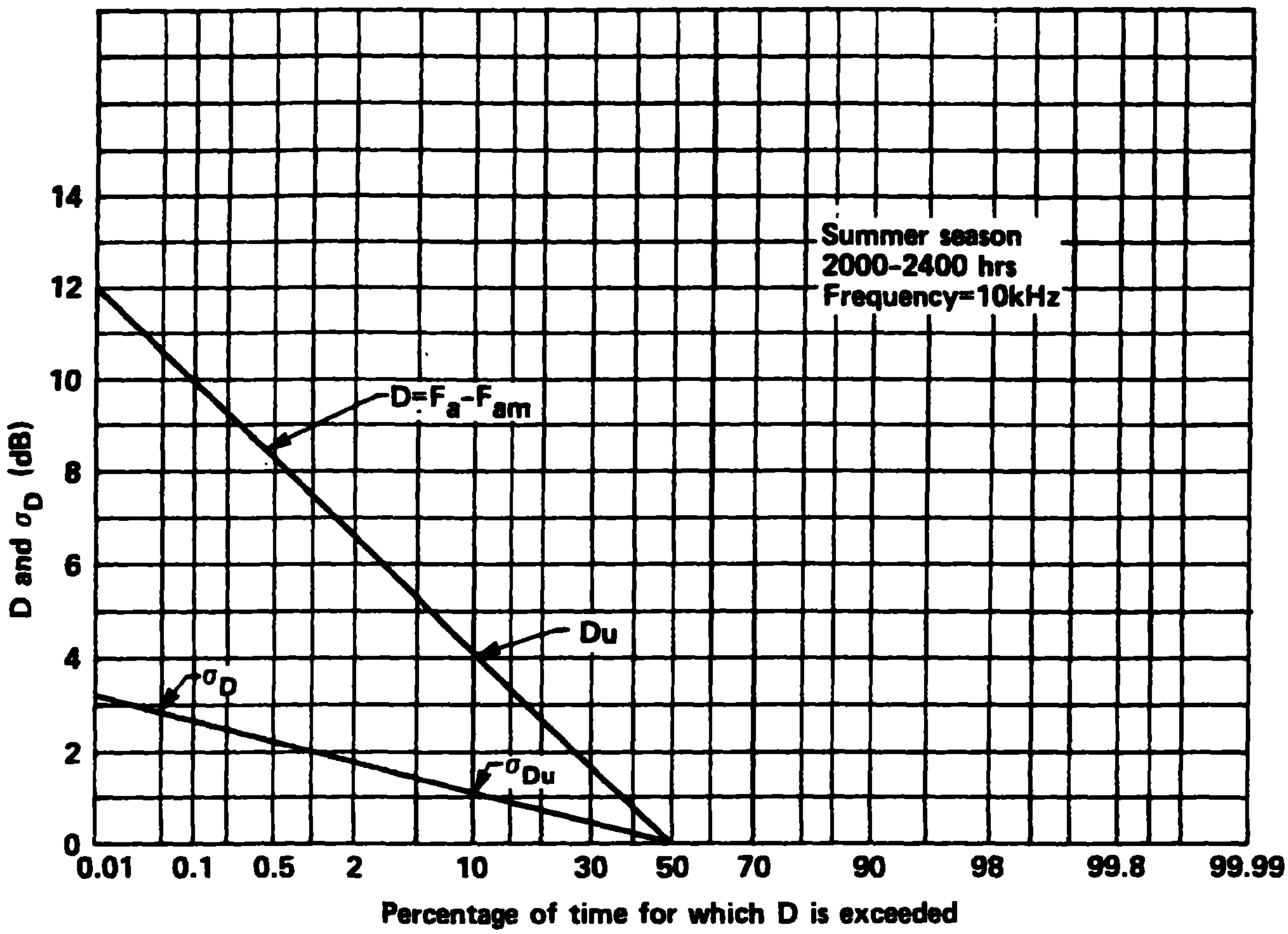

Figure 6 Expected values of D and their standard deviations, $^{\sigma}D$.

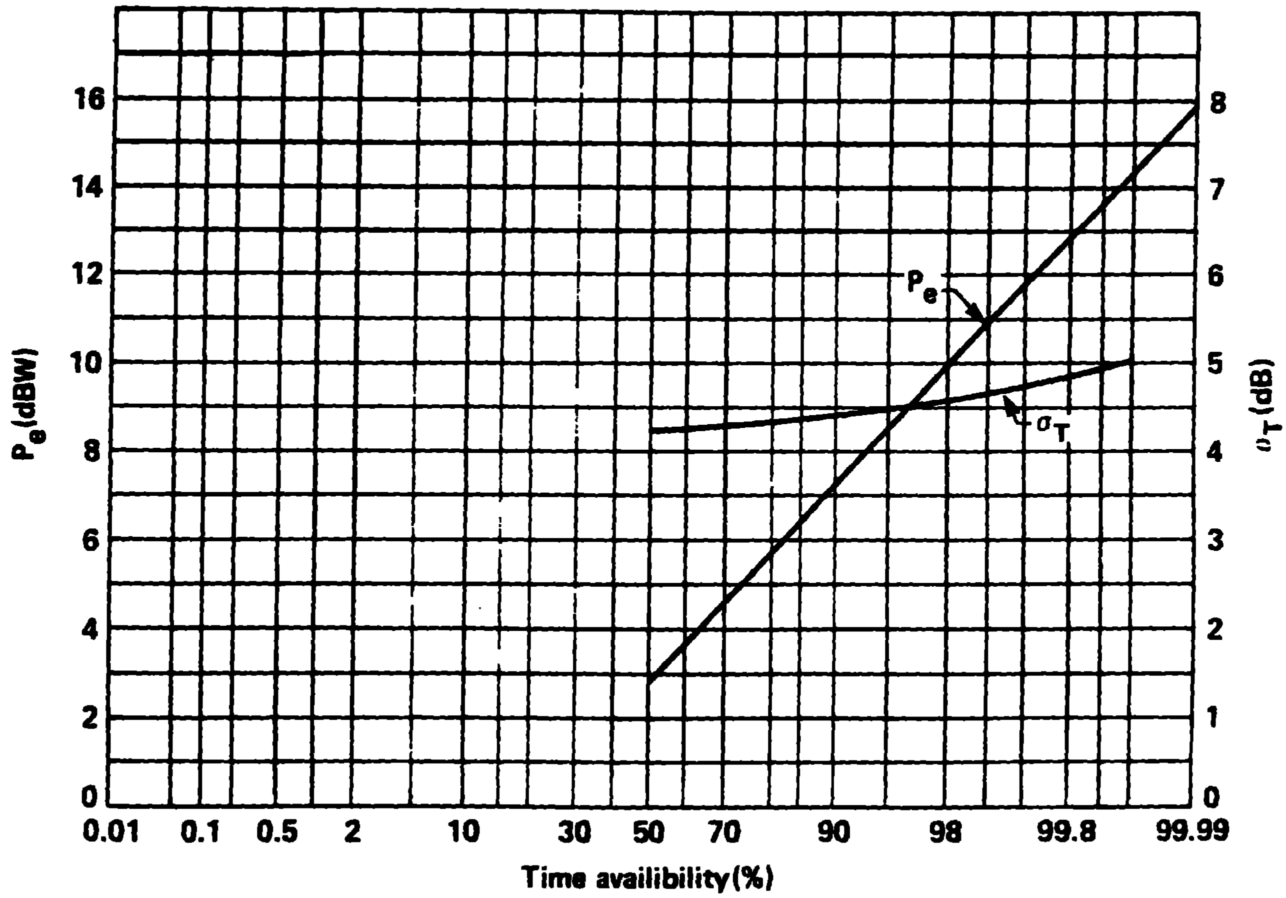

Figure 7 Expected values of P_e and their standard deviations, $^{\sigma}$T.

σ_P = standard error of achieving the expected received power (signal), assumed to be 2 dB.

σ_r = uncertainty in required signal-to-noise ratio, assumed to be 2 dB.

σ_Δ = 1 dB, from equations and coefficients given in CCIR 332, 1963.

σ_{Fam} = 3.1 dB from Fig. 1.

σ_D = standard deviation of D, which is a function of the required percentage time of operation (Fig. 6).

Assuming the errors are uncorrelated, the total uncertainty, σ_T, is

$$\sigma_T = \left(\sigma_p^2 + \sigma_r^2 + \sigma_\Delta^2 + \sigma_{Fam}^2 + \sigma_D^2\right) \quad , \tag{12}$$

and is plotted in Fig. 7. For any given value of received power, P, the time availability can be found as a function of service probability from

$$t = \frac{(P - P_e)}{\sigma_T} \tag{13}$$

where t is the standard normal deviate, and is plotted as a function of service probability in Fig. 8. Figure 9 shows the time availability as a function of service probability for various values of received power. This method of presenting the final results is quite commonly used and does provide the system analyst with a quick description of system performance.

If a probability of only 0.5 is required that a specified time availability will be achieved, then t = 0, $P = P_e$, and the powers are given by Fig. 7. If, however, we had 10 dBW (P), then, since a time availability of 0.99 would require P_e to be 11 dBW, we have

$$t = \frac{(10 - 11)}{4.75} = -0.21 \quad , \tag{14}$$

which, from Fig. 8, results in a service probability of 0.4. Similarly, for the same 10 dBW received power, the same Grade of Service would be achieved (or bettered) 80% of the time at a confidence level (service probability) of 0.83. Some representative curves of time availability versus service probability are shown in Fig. 9.

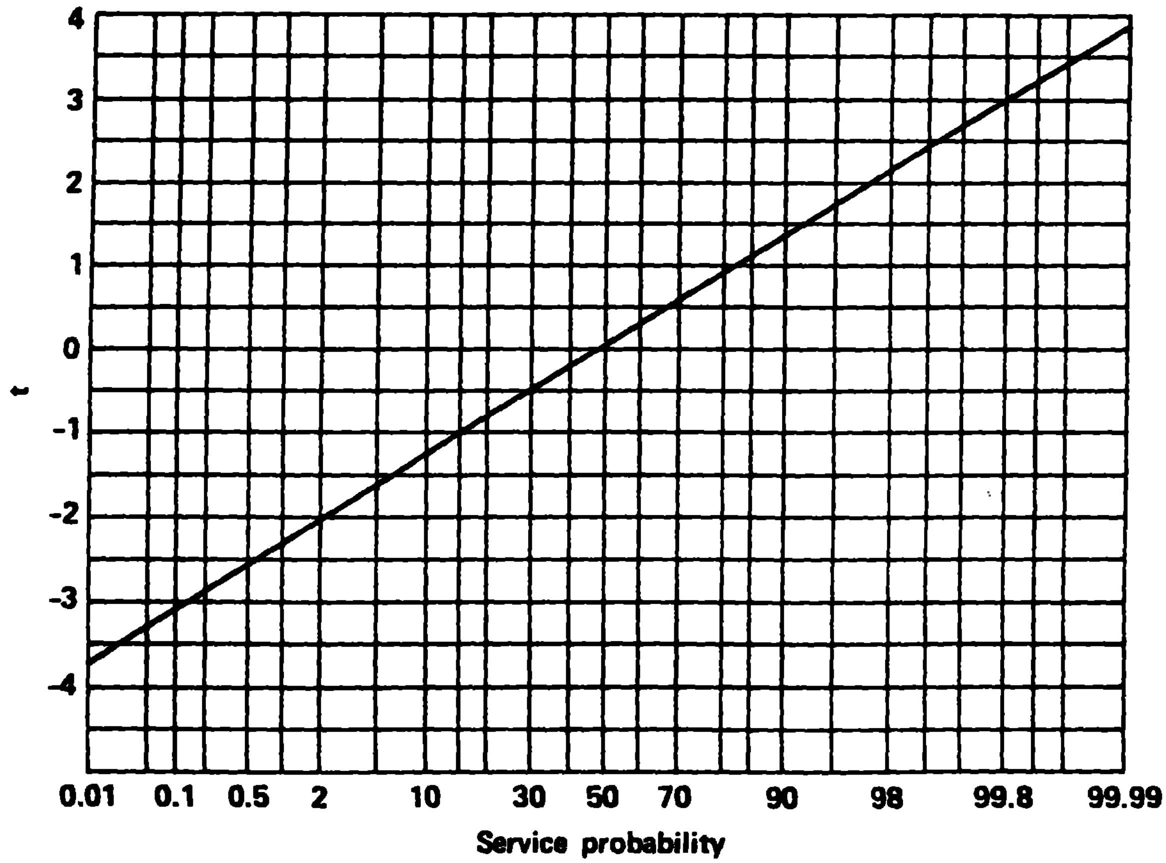

Figure 8 Service probability as a function of the standard normal deviate, t.

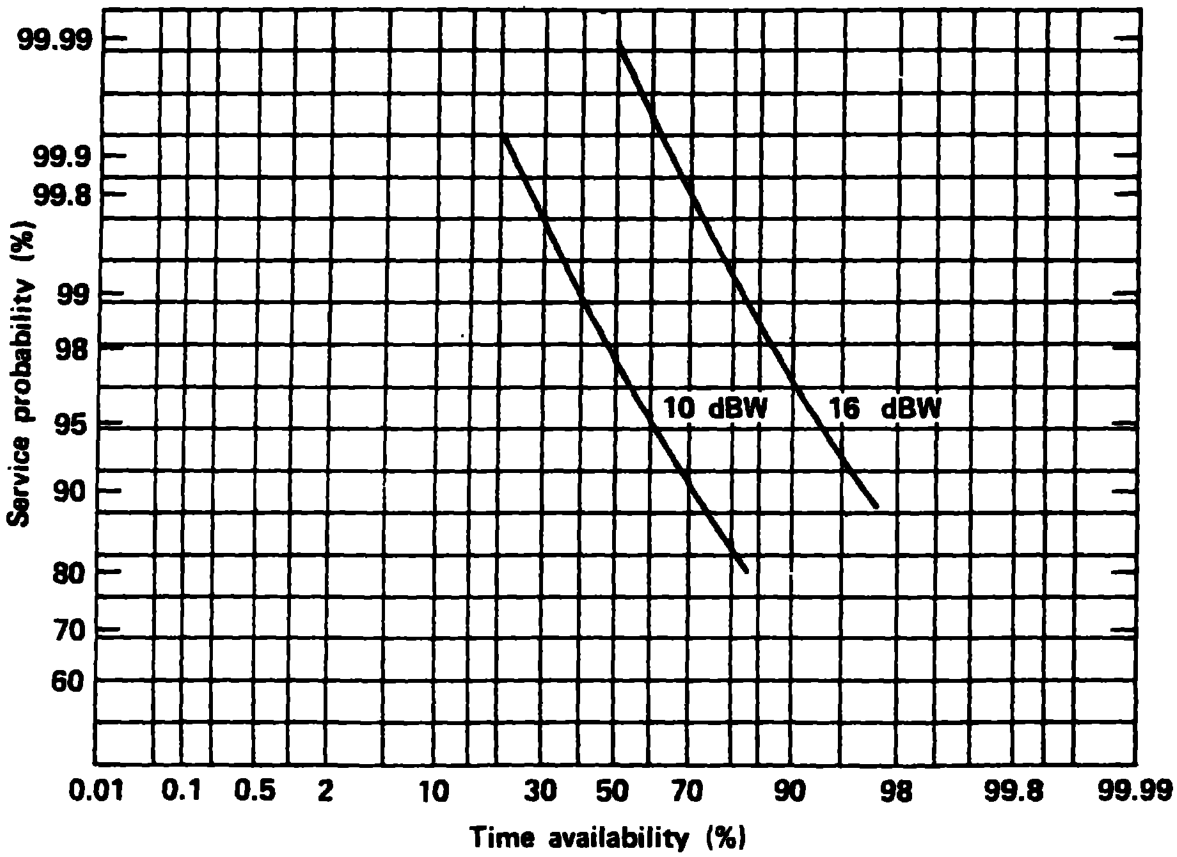

Figure 9 Service probability vs. time availability for different values of received power.

The preceding analysis applies to all atmospheric noise-limited systems. A number of additional assumptions may be made which can simplify the procedure; however, they must be clearly stated and the analytical results taken in that light.

APPENDIX 3
SELECTED MILITARY COMMUNICATION SYSTEMS - A SYNOPSIS

PRIMARY ALERT SYSTEM (PAS) - Current

- o Voice System
- o Leased Telephone Lines
- o Reserved for EAM Transmissions
- o Patched to NMCC for EAM Transmissions

HF RADIO SYSTEM - Current

- o Voice System
- o Single Sideband HF Radio System
- o Used for normal SAC long range radio communication
- o SAC relays EAMs over this system

UHF RADIO SYSTEM - Current

- o Voice System
- o UHF radio air to ground
- o Used to coordinate ABNCP and ALCC activity with M^2 LCF
- o Modified by Rivet Switch Program (SPO/AFCS)
  - Reduce bandwidth from 100 kHz to 25 kHz (ITU Treaty)
  - Modernize hardware (tubes to solid state)

STRATEGIC AIR COMMAND CONTROL SYSTEM (SACCS) - Current

- o Digital - 2400/1200 BPS
- o Leased Telephone network
- o Maximum message length (EAM) - 440 character (2 pack)
- o Normal Minuteman LCF/SAC communication system
- o SAC relays EAM's over this system
- o SACDIN will replace in 1980s.

SAC DIGITAL NETWORK (SACDIN) (SPO/ESD) - New

- Digital - 2400 BPS
- Switched telephone network - AUTOVON
- Maximum message length (EAM) - 64, K characters (256 pack)
- Normal Minuteman LCF/SAC communication system
- SAC relays EAM over this system
- Replaces SACCS in 1980s.

SURVIVABLE LOW FREQUENCY COMMUNICATION SYSTEM (SLFCS) (487L) - Current

- Digital 5/50/75 BPS
- VLF radio
- Used for emergency communications to SAC HQ to forces
- SAC relays EAM over this system
- Modified by project 616A (SPO/ESD)
    - Reduce receiver bandwidth
    - Add error correction
    - Install KG 38 crypto system
    - Add AJ capability
    - Hardened critical circuits

AF SATELLITE COMMUNICATION SYSTEM (AF SATCOM) (SPO/SAMSO) - Current

- Digital - 75 BPS
- VHF radio
- Maximum message length (EAM)
- Automatic collection of force status for SAC HQ
- EAM repeatedly broadcast by satellite for extended period

MILITARY SATELLITE (MILSTAR) - New

- Secure digital 75 BPS
- EHF radio, 20-40 GHz
- Message length
- Collection of force status for SAC HA/H.A.
- EAM repeatedly broadcast by satellite for extended periods

GROUND WAVE EMERGENCY NETWORK (GWEN) - New

- o Digital -75 BPS
- o Radio
  - VHF entry
  - LF relay
- o Used for emergency communications
  - Command networking - NORAD to CINCSAC, etc.
  - SINCSAC TO SAC SIOP forces
- o SAC relays EAM over system
- o Two phase deployment
  - Thinline
  - Full conus network

MINIMUM ESSENTIAL EMERGENCY COMMUNICATIONS NETWORK (MEECN)

- o Grouping of five systems
  - ERCS: Emergency Rocket Communication System
  - SATCOM: Satellite Communications including AFSATCOM and FLEETSATCOM
  - LF/VLF: Includes SLFCS
  - PACCS: Post Attack C and C System
  - HF: 3.5 to 30 MHz, one way to LCFs (receive only)
- o Subscribers include Strategic Forces such as minuteman, submarines, etc.

APPENDIX 4
EMP PROTECTION ENGINEERING

There are a large number of EMP practitioners and many predictive techniques for estimating EMP effects. None of these techniques are the last word in predictive capability. They are limited in their frequency regimes--they may be quasi-static or low frequency only as in transmission line models. They are limited in the level of geometric complexity--none at present treat the "spaghetti-like" interior of an aircraft for example. Or they are limited as to the aspect of the problem that they treat--some EMP analyses worry only about device failure and treat the outside world as being reduced to a set of pin voltages. A few practitioners within the EMP community have been able to pull together a variety of these techniques, so that they can make predictions over a broad frequency range for a complex system. Unfortunately, these predictions are generally only good to the extent that they predict ballpark (as bad as ±20 dB) responses. The underlying phenomenology is only now being illuminated (King et al., 1984) for relatively simple systems. It is expected that in a few years this phenomenological understanding will improve the selection of EMP predictive tools to where better predictions are made. In the meantime, not all is lost. Good design practices have emerged from the EMP community's limited understanding, past predictions and, most importantly, past and on-going experiments.

EMP design requirements can be specified for a particular system. Predictions can then be made for this particular system and potential weakness identified and corrected. The expected hardness can then be verified via experiment. An example of one of the more effective hardening approaches is given below. It uses the notion of topological shielding, developed by Vance (1980) and Tesche (1978), in which a system is broken up into zones that are separated by conducting boundaries. Each boundary is viewed as a potential Faraday cage. It can be made to approximate a Faraday cage by

- o closing off apertures -

  with wire screens or "egg crate" grills,
- o filtering incoming power or communication lines, and
- o observing recommended grounding procedures.

It is then possible to design system hardness systematically with a high degree of assurance by following these well established and tested techniques.

In this section of the Appendix, we present a brief description of the methodology used by the Defense Communication Agency (DCA) to develop protection specifications for the facilities, equipment and related components of the Defense Switched Network (DSN) (Miletta et al., 1982). The specifications lend to design practices which are also provided in the handbook, and which are considered mandatory for the DSN. The design practices will not be examined in detail; our interest here lies in reviewing the methodology used in obtaining threat levels and degrees of protection required at the various levels throughout the DSN. This procedure aids us in illustrating the type of approach that should be used to insure that any and all of the potential communication systems for the deep base will be protected against EMP.

Essentially, DCA devised a zonal structure that depends upon the fact that communication facilities do have several regions of electromagnetic (EM) environment separated by barriers, such as building walls, cabinet shields, etc. A shielding and grounding topology was developed such as that illustrated in Fig. 1, where the natural shielded regions are represented by equipotential zones separated by EM barriers (shields). Ideally, the shields are continuous, closed, and highly conducting faraday shields. In practice, however, they may be compromised by penetrating conductors or apertures.

In the DCA zonal approach, five functional elements are identified, with their relationship to the zone boundaries given as follows:

1. Components (zone 2/3 boundary and zone 3).
2. Equipment (zone 1/2 boundary and zone 2).
3. Intrasite (in-plant, zone 1).
4. Site housing (zone 0/1 boundary).
5. Plant exterior (zone 0).

The numerical order indicates relative importance. Each of the above elements represents a physical region where hardening is required. The design

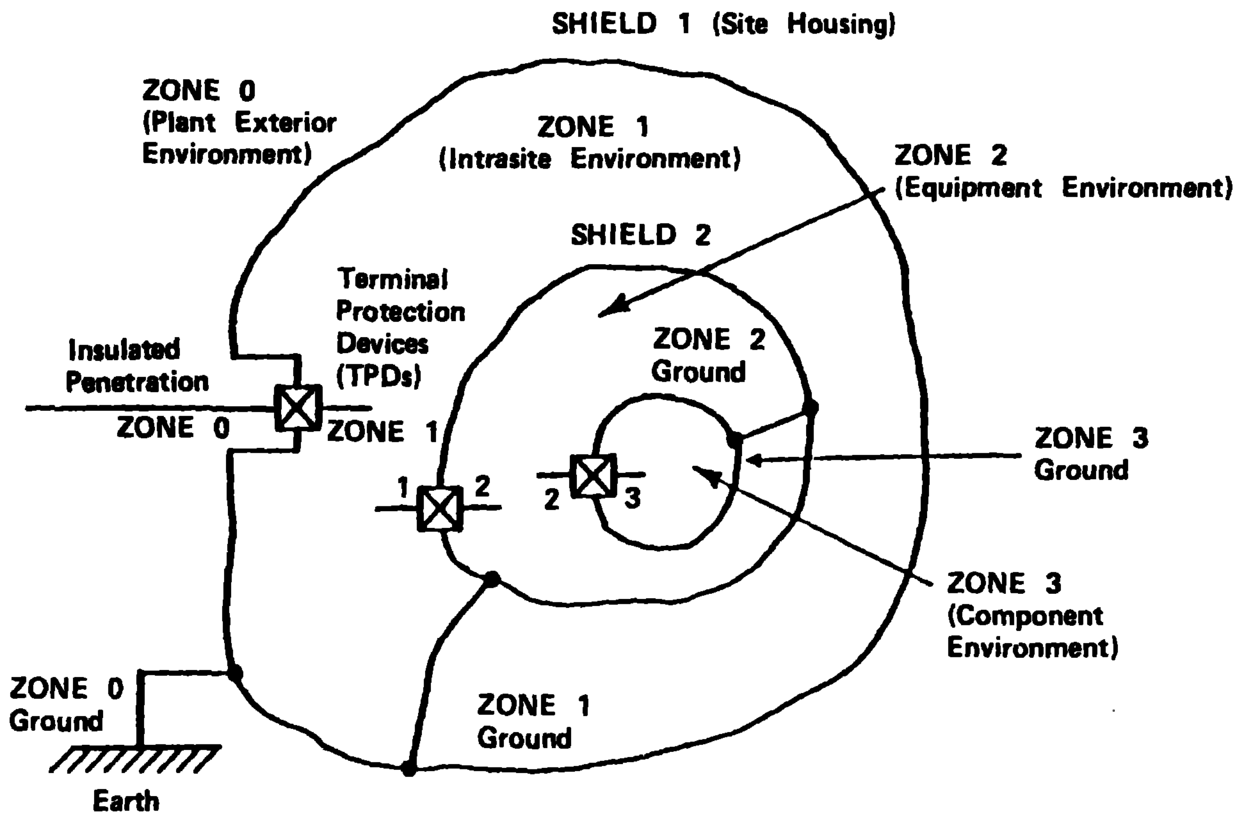

Figure 1. Environmental zones in a complex facility (after Miletta et al., 1982)

practices which provide hardening can be separated into the following categories:

1. Shielding
2. Isolation
3. Transient suppression
4. Common-mode rejection
5. Grounding

The above design practices are most effectively applied to the zone boundary, but can also be applied within zone 0.

DCA uses energy as the measure of the threshold of component parts, components, equipment and as a measure of the severity of the threat. A quantity, dBJ, is defined as

$$\mathrm{dBJ} \triangleq 10 \log_{10}(E) \qquad > 1 \text{ Joule} \quad , \tag{1}$$

where dBJ is the energy in dB and E is the energy in Joules (J). The allocation strategy DCA uses for the design practices is based on a minimum damage threshold of 10 μJ (-50 dBJ). The worst-case threat energies are shown in Table 1.

Detailed specifications for the degree of protection required were developed for the points of entry (POEs) to each functional element area. These specifications reflect the fact that no element allocation is over 35 dBE ($\triangleq 10 \log_{10} E_{in}/E_{out}$), and incorporate a safety margin due to the following:

1. Worst-case minimum thresholds were used to provide the lower bound for the protection allocations.
2. Worst-case POE threats were used to provide the upper bound for the allocation.
3. The site housing element was considered to be a hardening bonus area.

Points of Entry	Worse-case energy values
AC power	70 dBJ
DC power	60 dBJ
Signal cables	50 dBJ
Control cables	50 dBJ
Waveguides	50 dBJ
Antenna	50 dBJ
Water	25 dBJ
Sewage	25 dBJ
Fuel	25 dBJ
Air-conditioning	25 dBJ
Grounding	50 dBJ

Table 1

Worst case threshold energies for EMP protection (Miletta et al., 1982). Units for energy are defined by dBJ $\triangleq \log_{10}$ (E) where E is in Joules and dBJ is energy in dB > 1 Joule. Most of energy is in the 10^4 to 10^9 Hz range.

The specifications are given in Tables 2 through 6*. Different EMP waveforms are considered. These include double exponentials (xx) of the form

$$S(t) = \pm\,(\text{amplitude})\,\left[\exp(-10^5 t) - \exp(rt)\right] \quad , \tag{2}$$

where

$$r = -(0.43)\,(\text{rate of rise})/(\text{amplitude}) \quad , \tag{3}$$

and single (ds) or multiple (mds) damped sinusoids of the form

$$S(t) = (\text{amplitude})\,\left[\exp(-\alpha t)\right]\left[\sin(2\pi f_o t)\right] \quad . \tag{4}$$

The parameters of these waveshapes are given in Tables 2 through 6. In Table 7, a list of MIL-STD documents for EMP-Related EM Standards is given.

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* Site housing design practices provide a surplus safety margin beyond the preset requirements. Therefore, they were not considered when establishing the specifications for the functional intrasite elements.

Table 2 Specifications for Plant Exterior (after Milletta et al., 1982)

Points of entry	Energy	Amplitude	Impedance (ohms)	Rate of rise	Bandwidth (MHZ)	Wave-shape
AC power	70 dBJ	10 MV	500	0.5 MV/ns	0.01 to 50	xx[a]
DC power	60 dBJ	2 MV	300	0.1 MV/ns	0.01 to 50	xx
Signal cables	50 dBJ	0.7 MV	300	30 kV/ns	0.01 to 50	xx
Control cables	50 dBJ	0.7 MV	300	30 kV/ns	0.01 to 50	xx
Waveguide	50 dBJ	0.5 MV	100	20 kV/ns	0.1 to 100	xx
Antenna	50 dBJ	0.7 MV	300	30 kV/ns	0.01 to 100	xx
Water	25 dBJ	10 kV	20	0.2 kV/ns	0.01 to 10	xx
Sewage	25 dBJ	10 kV	20	0.2 kV/ns	0.01 to 10	xx
Fuel	25 dBJ	10 kV	20	0.2 kV/ns	0.01 to 10	xx
Air-conditioning	25 dBJ	10 kV	20	0.2 kV/ns	0.01 to 10	xx
Grounding	50 dBJ	200 kV	20	20 kV/ns	0.01 to 50	xx
Structure—diffused field	0 dBJ	50 kV/m	377	10 kV/m/ns	0.1 to 100	xx
Structure—conducted	25 dBJ	10 kV	20	0.2 kV/ns	0.01 to 10	xx
Apertures	0 dBJ/m^2	50 kV/m	377	10 kV/m/ns	0.1 to 100	xx

[a]xx – Double Exponential

Table 3 Specifications for Site Housing (after Milletta et al., 1982)

Points of entry	Energy	Amplitude	Impedance (ohms)	Rate of rise	Bandwidth (MHz)	Wave-shape
AC power	35 dBJ	100 kV	100	1 kV/ns	0.1 to 10	xx[a]
DC power	35 dBJ	100 kV	100	1 kV/ns	0.1 to 10	xx
Signal cables	30 dBJ	50 kV	100	1 kV/ns	1 to 10	DS[b]
Control cables	30 dBJ	50 kV	100	1 kV/ns	1 to 10	DS
Waveguide	30 dBJ	20 kV	20	1 kV/ns	1 to 10	DS
Antenna	50 dBJ	0.7 MV	300	30 kV/ns	0.01 to 100	xx
Water	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Sewage	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Fuel	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Air-conditioning	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Grounding	30 dBJ	20 kV	20	1 kV/ns	0.01 to 10	xx
Structure—diffused field	0 dBJ/m^2	50 kV/m	377	10 kV/m/ns	0.1 to 100	xx
Structure—conducted	5 dBJ	1 kV	20	100 V/ns	1 to 10	DS
Apertures	0 dBJ/m^2	50 kV/m	377	10 kV/m/ns	0.1 to 100	xx

[a]xx – Double Exponential

[b]DS – Damped Sinusoid, 1/a = 6ms

Table 4 Specifications for Intrasite (in-plant) (after Milletta et al., 1982)

Points of entry	Energy	Amplitude	Impedance (ohms)	Rate of rise	Bandwidth (MHz)	Wave-shape
AC power	35 dBJ	100 kV	100	1 kV/ns	0.1 to 10	xx[a]
DC power	35 dBJ	100 kV	100	1 kV/ns	0.1 to 10	xx
Signal cables	30 dBJ	50 kV	100	1 kV/ns	1 to 10	DS[b]
Control cables	30 dBJ	50 kV	100	1 kV/ns	1 to 10	DS
Waveguide	30 dBJ	20 kV	20	1 kV/ns	1 to 10	DS
Antenna	50 dBJ	0.7 MV	300	30 kV/ns	0.01 to 100	xx
Water	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Sewage	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Fuel	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Air-conditioning	5 dBJ	1 kV	20	10 V/ns	0.01 to 10	xx
Grounding	30 dBJ	20 kV	20	1 kV/ns	0.01 to 10	xx
Structure—diffused field	0 dBJ/m^2	50 kV/m	377	10 kV/m/ns	0.1 to 100	xx
Structure—conducted	5 dBJ	1 kV	20	100 V/ns	1 to 10	ns
Apertures	0 dBJ/m^2	50 kV/m	377	10 kV/m/ns	0.1–100	xx

[a]xx — Double Exponential

[b]DS — Damped Sinusoid, 1/a = 6 ms

Table 5 Specifications for Equipment (after Milletta et al., 1982)

Points of entry	Energy	Amplitude	Impedance (ohms)	Rate of rise	Bandwidth (MHz)	Wave-shape	Comments
AC power	-20 dBJ	1 kV	100	10 V/ns	1 to 15	MDS[a]	
DC power	-20 dBJ	1 kV	100	10 V/ns	1 to 15	MDS	f_o = 1, 2.5, 5, 10, 15 MHz
Signal cables	-20 dBJ	1 kV	100	10 V/ns	1 to 15	MDS	1/a = 6 μs
Control cables	-20 dBJ	1 kV	100	10 V/ns	1 to 15	MDS	
Antenna	-20 dBJ	1 kV	100	100 V/ns	0.01 to 100	xx[b]	
Grounding	-20 dBJ	0.4 kV	20	5 V/ns	0.1 to 10	xx	
Structure—diffused field	-30 dBJ/m^2	1.6 kV/m	100	160 V/m/ns	1 to 10	MDS	f_o = 1 MHz, 10 MHz
Apertures	-30 dBJ/m^2	1.6 kV/m	100	160 V/m/ns	1 to 10	MDS	1/a = 1 μs

[a]MDS – Multiple Damped Sinusoid

[b]xx – Double Exponential

Table 6 Specifications for Components (after Milletta et al., 1982)

Points of entry	Energy	Amplitude	Impedance (ohms)	Rate of rise	Bandwidth (MHz)	Wave-shape	Comments
AC power	0 dBJ	10 kV	100	100 V/ns	1 to 15	MDS[a]	
DC power	0 dBJ	10 kV	100	100 V/ns	1 to 15	MDS	f_o = 1, 2.5, 5, 10, 15 MHz
Signal cables	0 dBJ	10 kV	100	100 V/ns	1 to 15	MDS	1/a = 6 μs
Control cables	0 dBJ	10 kV	100	100 V/ns	1 to 15	MDS	
Antenna	15 dBJ	100 kV	300	20 V/ns	0.01 to 100	xx[b]	
Grounding	0 dBJ	2 kV	20	20 V/ns	0.1 to 10	xx	
Structure—diffused field	0 dBJ/m^2	50 kV/m^2	377	10 kV/m/ns	0.1 to 100	MDS	f_o = 1 MHz, 10 MHz
Apertures	0 dBJ/m^2	50 kV/m^2	377	10 kV/m/ns	0.1 to 100	MDS	1/a = 1 μs

[a]MDS – Miltiple Damped Sinusoid

[b]xx – Double Exponential

Table 7. EMP-Related EM Standards (Greenwell, R. A., private communication, 1985)

Number	Title	Originator	Revision In Work	Needs Revision for EMP
MIL-STD-188-124	Grounding, Bonding & Shielding for Common Long Haul/Tactical Communication Systems	AFSC/RADC	X	X
MIL-STD-461	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference	NAVELEX	X	X
MIL-STD-469	Radar Engineering Design Requirements; Electromagnetic Compatibility	NAVSEA		
MIL-STD-1310	Shipboard Bonding, Grounding and Other Techniques for Electromagnetic Compatibility and Safety	NAVSEA	X	X
MIL-STD-1377	Effectiveness of Cable Connector and Weapon Enclosure Shielding and Filters in Precluding Hazards of Electromagnetic Radiation to Ordnance; Measurements of	NAVSEA ORDNANCE		
MIL-STD-1385	Preclusion of Ordnance Hazards in Electromagnetic Fields; General Requirements for	NAVSEA ORDNANCE	X	X
MIL-STD-1395	Filters and Networks; Selection and Use of	NAVELEX	X	X
MIL-STD-1512	Electroexplosive Subsystems, Electrically Initiated; Design Requirements and Test Methods	AFSCI/ASD		X
MIL-STD-1541 (USAF)	Electromagnetic Compatibility Requirements for Space Systems	SPACE DIVISION		X
MIL-STD-1542 (USAF)	Electromagnetic Compatibility (EMC) and Grounding Requirements for Space Systems Facilities	SPACE DIVISION		X
MIL-STD-1605	Procedures for Conducting a Shipboard Electromagnetic	NAVSEA		X
MIL-STD-1857	Interface Survey (Surface Ship) Grounding, Bonding, and Shielding Design Practices	ARMY(CR)		X